Brian L. Winer
Center for Cosmology and Astroparticle Physics
The Ohio State University

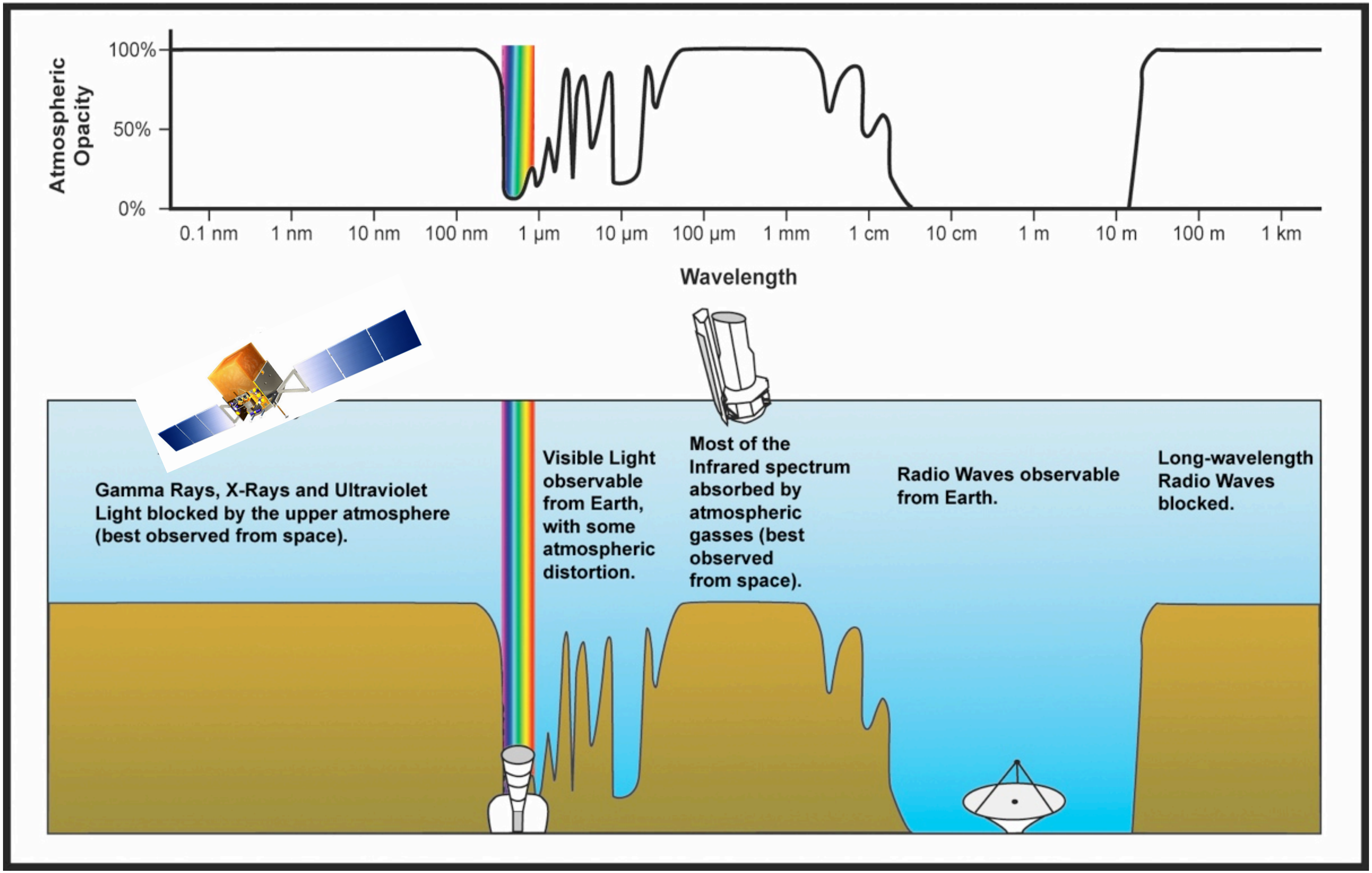
Representing the Fermi LAT Collaboration

Brookhaven Forum 2010

A Space-Time Odyssey

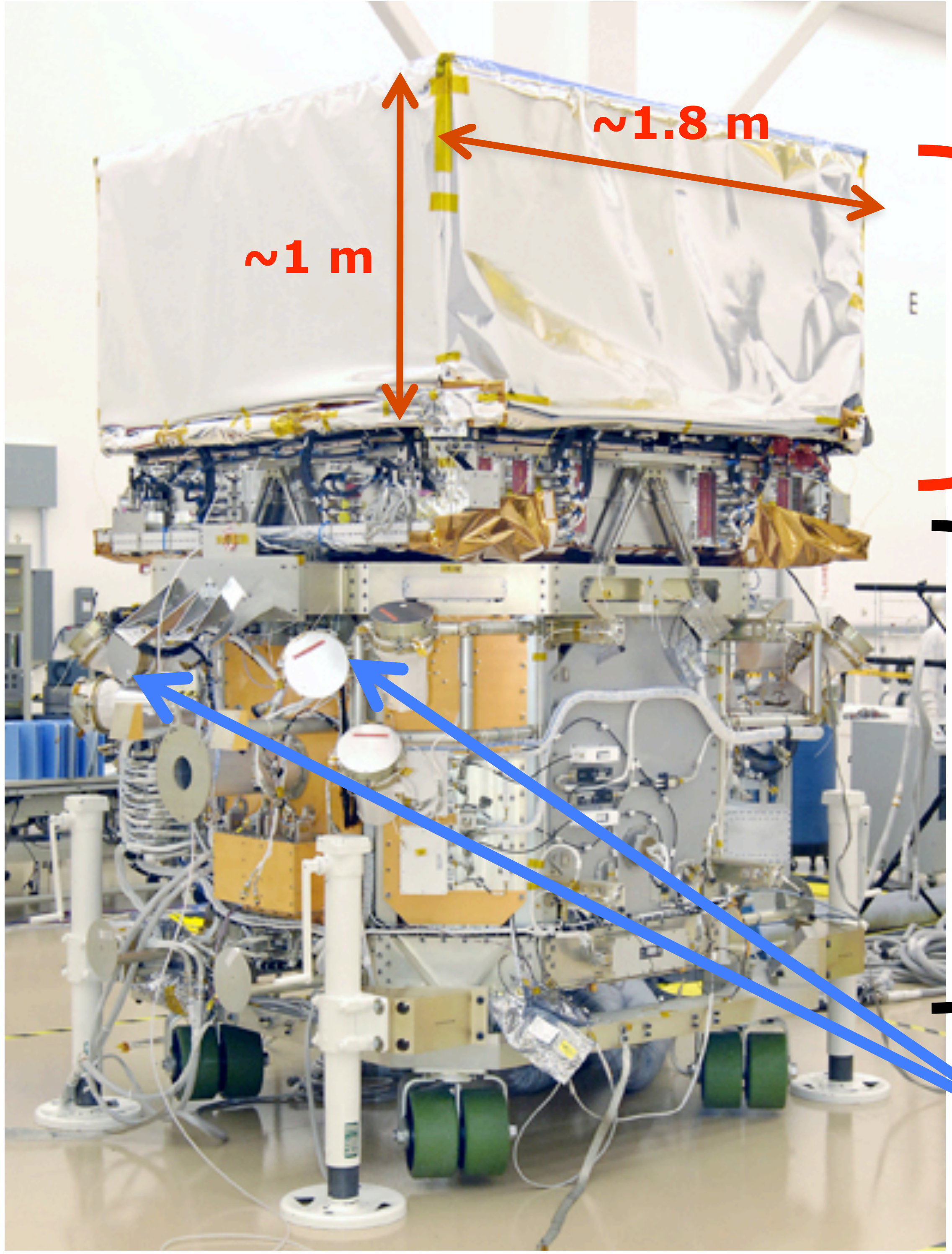
Hunting for Dark Matter with the Fermi Gamma-Ray Space Telescope

Where to place the observatory?



NASA Image

Fermi Observatory



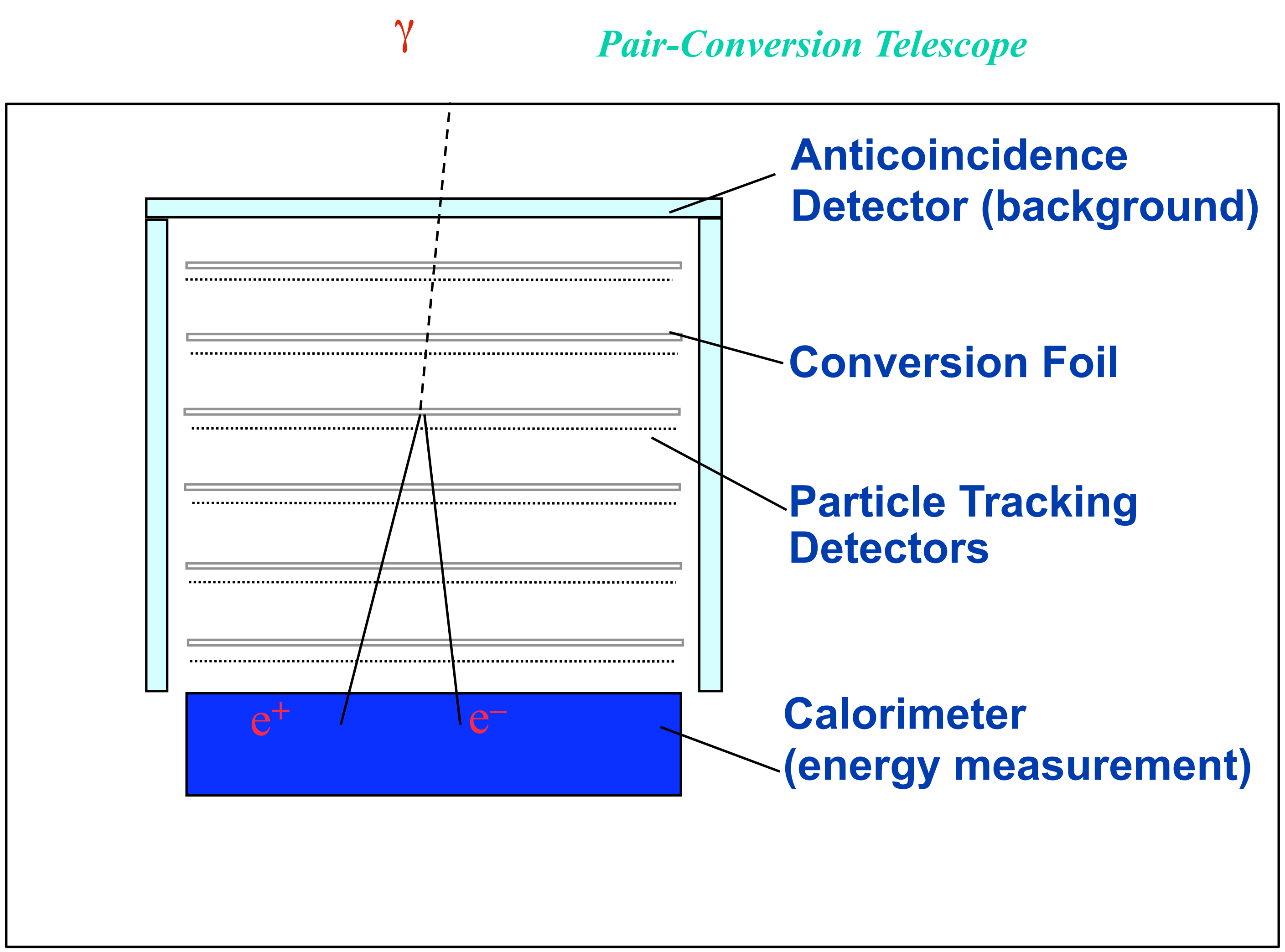
Large Area Telescope (LAT)
* High Energy Gamma Rays
* 20 MeV > E > ~300 GeV

Spacecraft

Gamma-Ray Burst Monitor
* GRB Detection.
* 10 KeV < E < 40 MeV

Detection Strategy

- High Energy Gamma tend to pair produce
- LAT Energy Range: 20 MeV -- ~300 GeV
- GBM: 8 keV -- -- 40 MeV



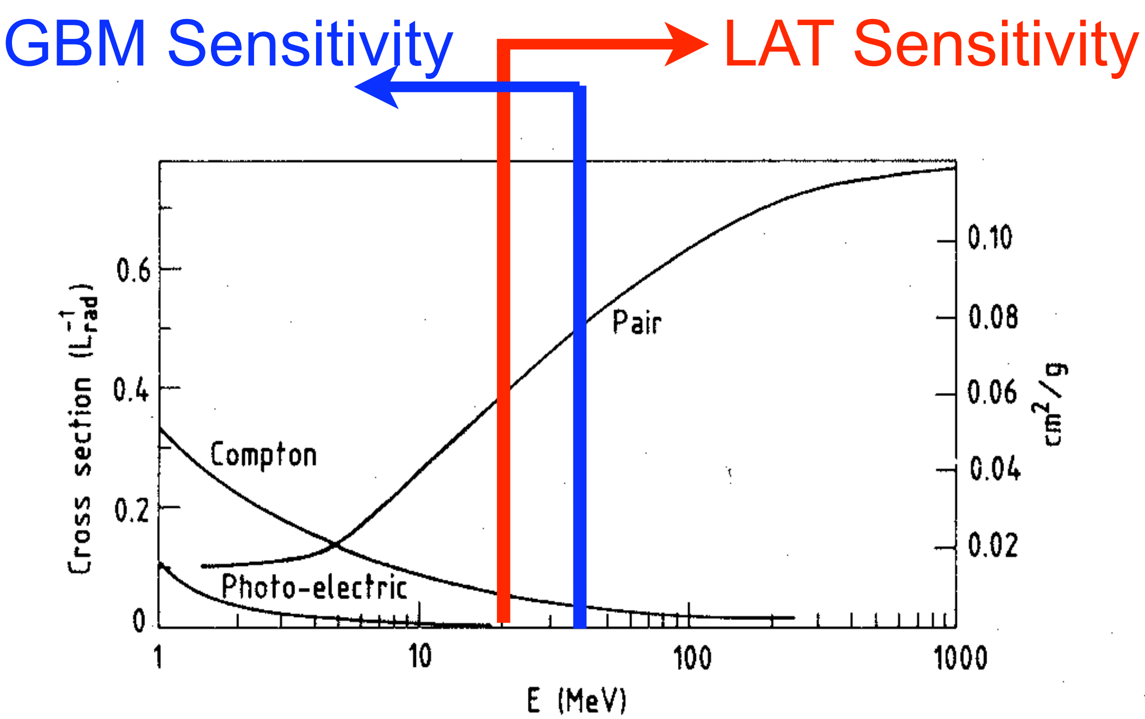
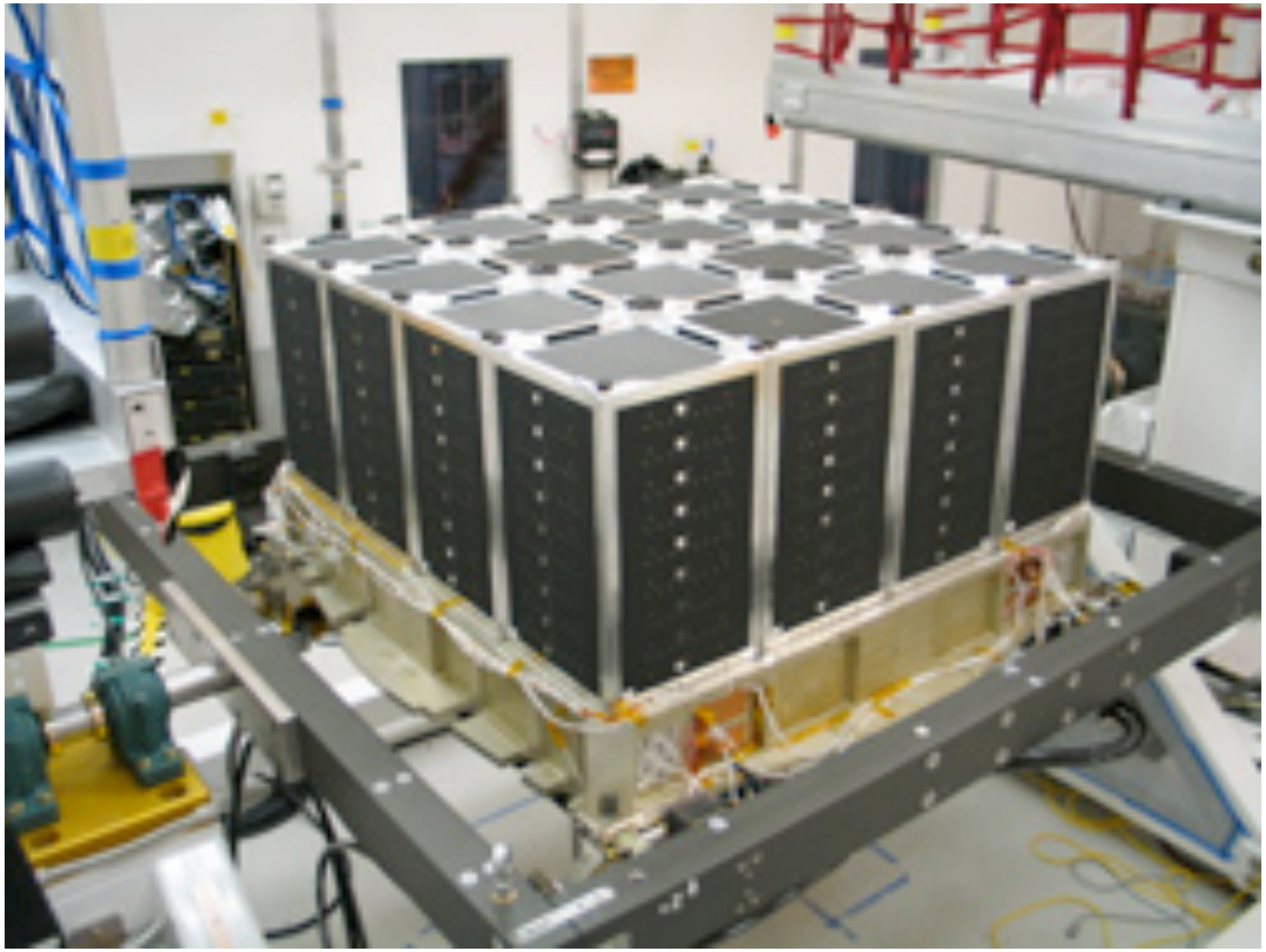


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

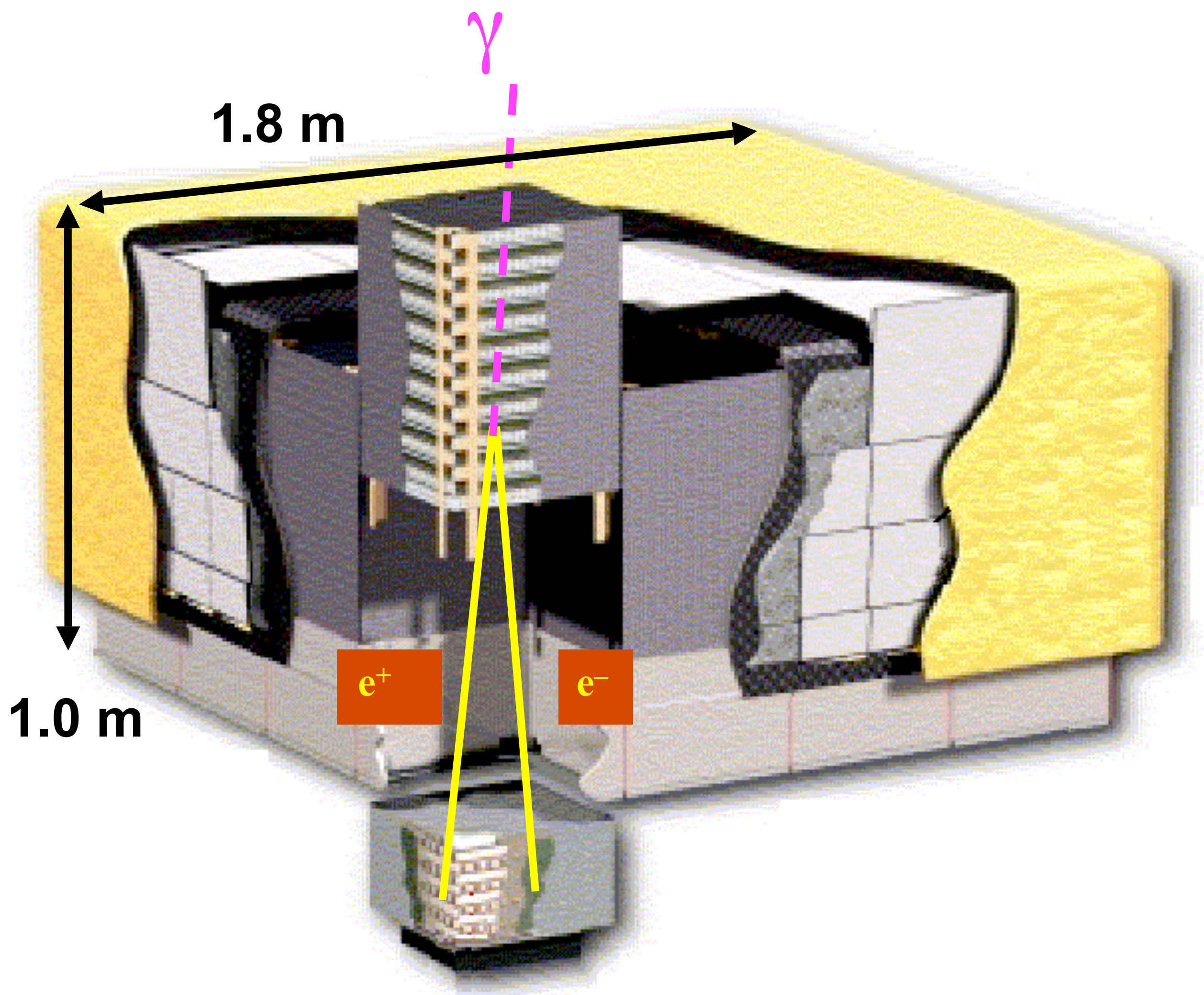
Pair Conversion Approach

- Veto Charge Particle Background
- Make gamma convert.
- Reconstruct directions of e+ e-
- Measure Energy e+ e-
- Reconstruct original direction and Energy of gamma.

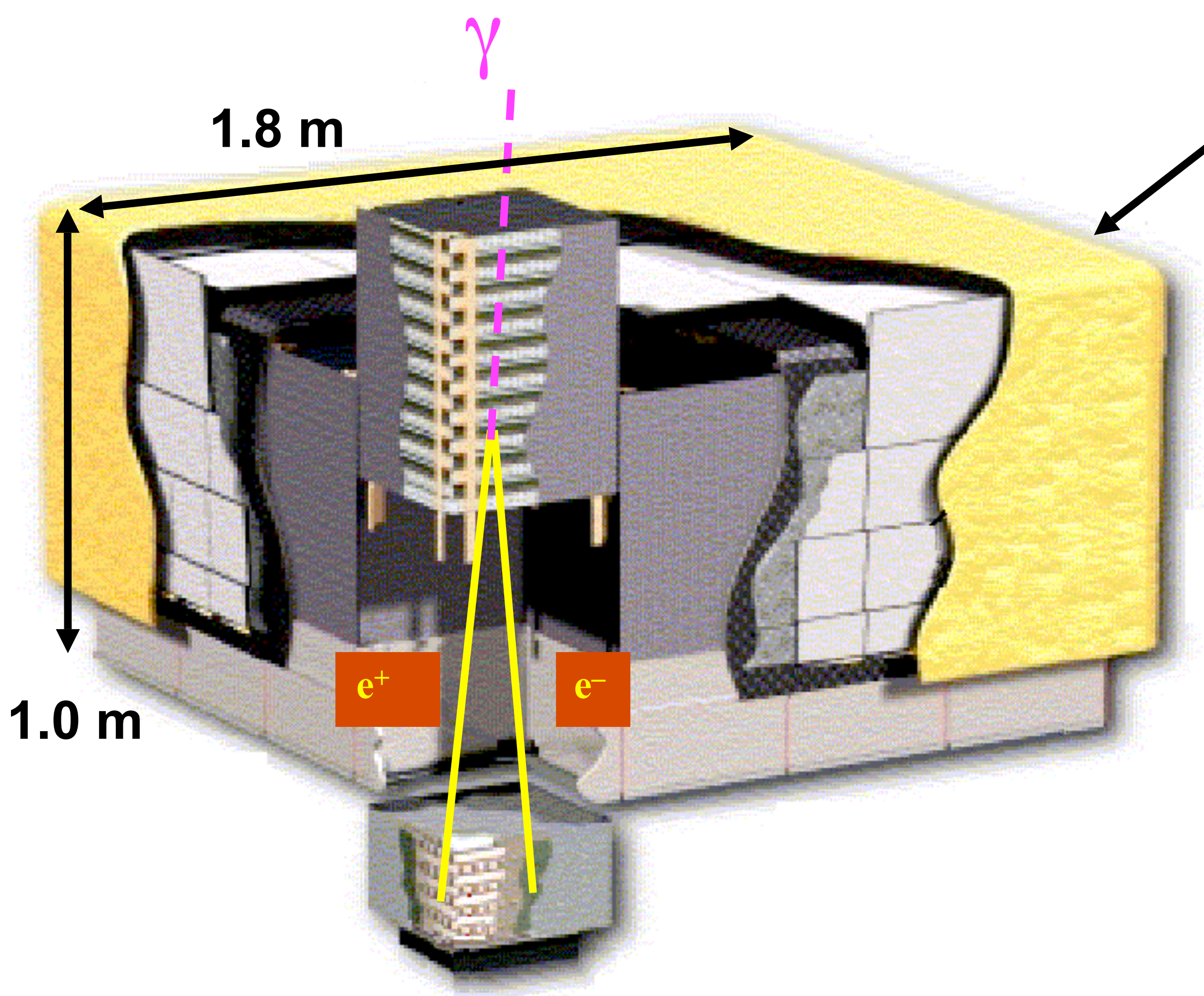
Fermi Large Area Telescope (LAT)



Fermi Large Area Telescope (LAT)

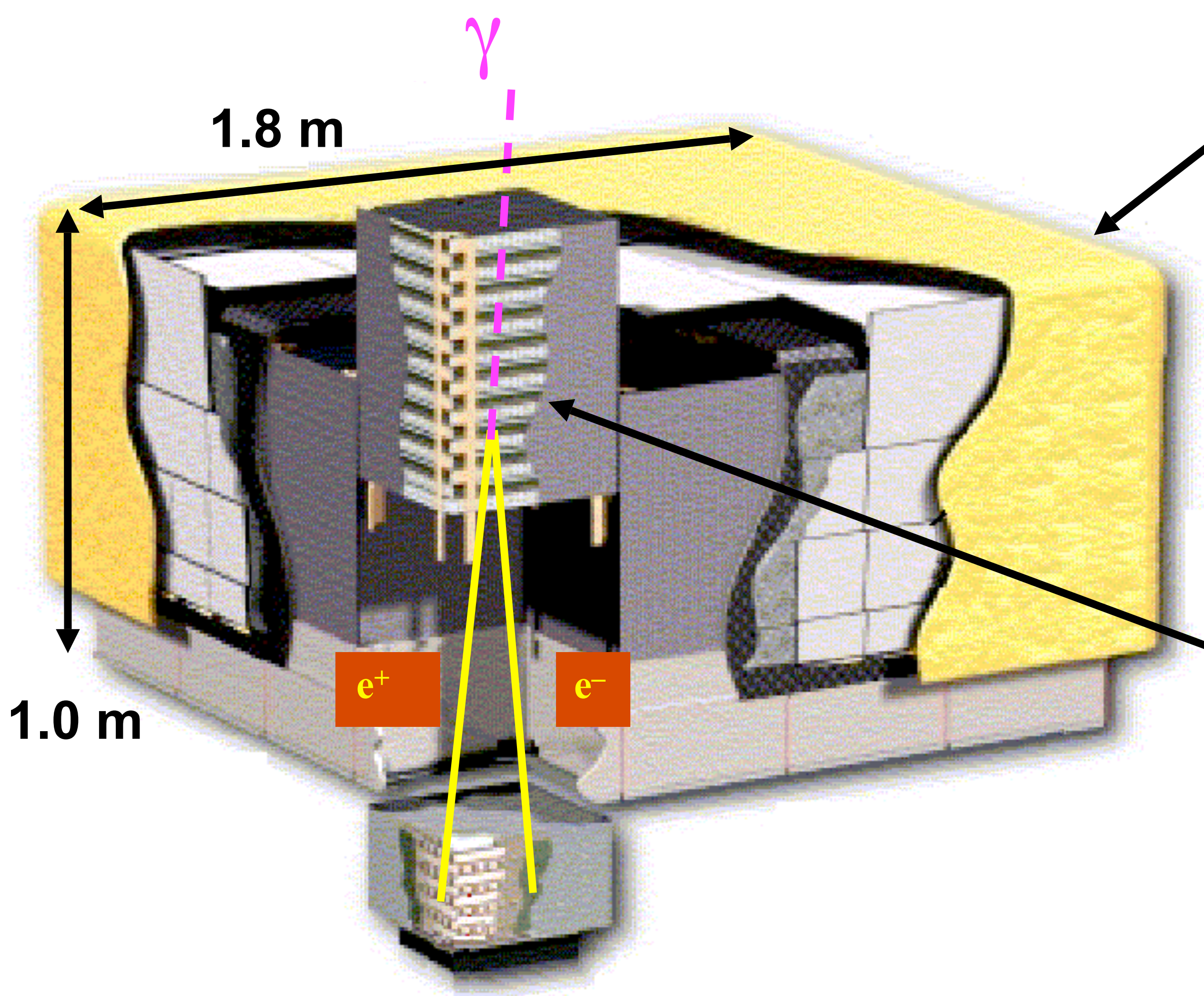


Fermi Large Area Telescope (LAT)



Anti-Coincidence Detector
- **4% R.L.**
- **89 scintillating tiles**
- **efficiency (>0.9997) for MIPs**

Fermi Large Area Telescope (LAT)



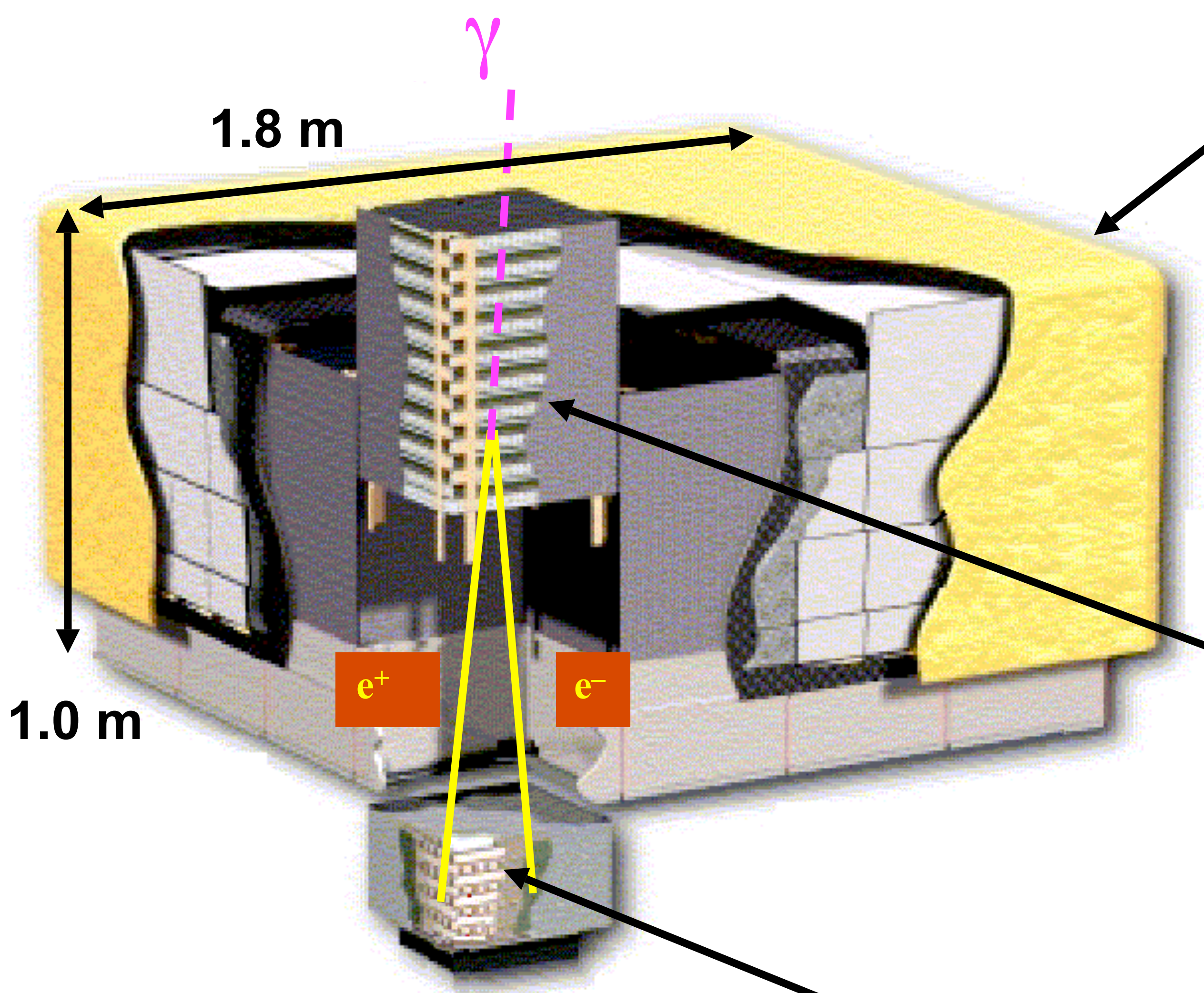
Anti-Coincidence Detector

- 4% R.L.
- 89 scintillating tiles
- efficiency (>0.9997) for MIPs

Tracking detector

- 16 tungsten foils (12x3%R.L.,4x18%R.L.)
- 18 pairs of silicon strip arrays
- 884736 strips (228 micron pitch)

Fermi Large Area Telescope (LAT)

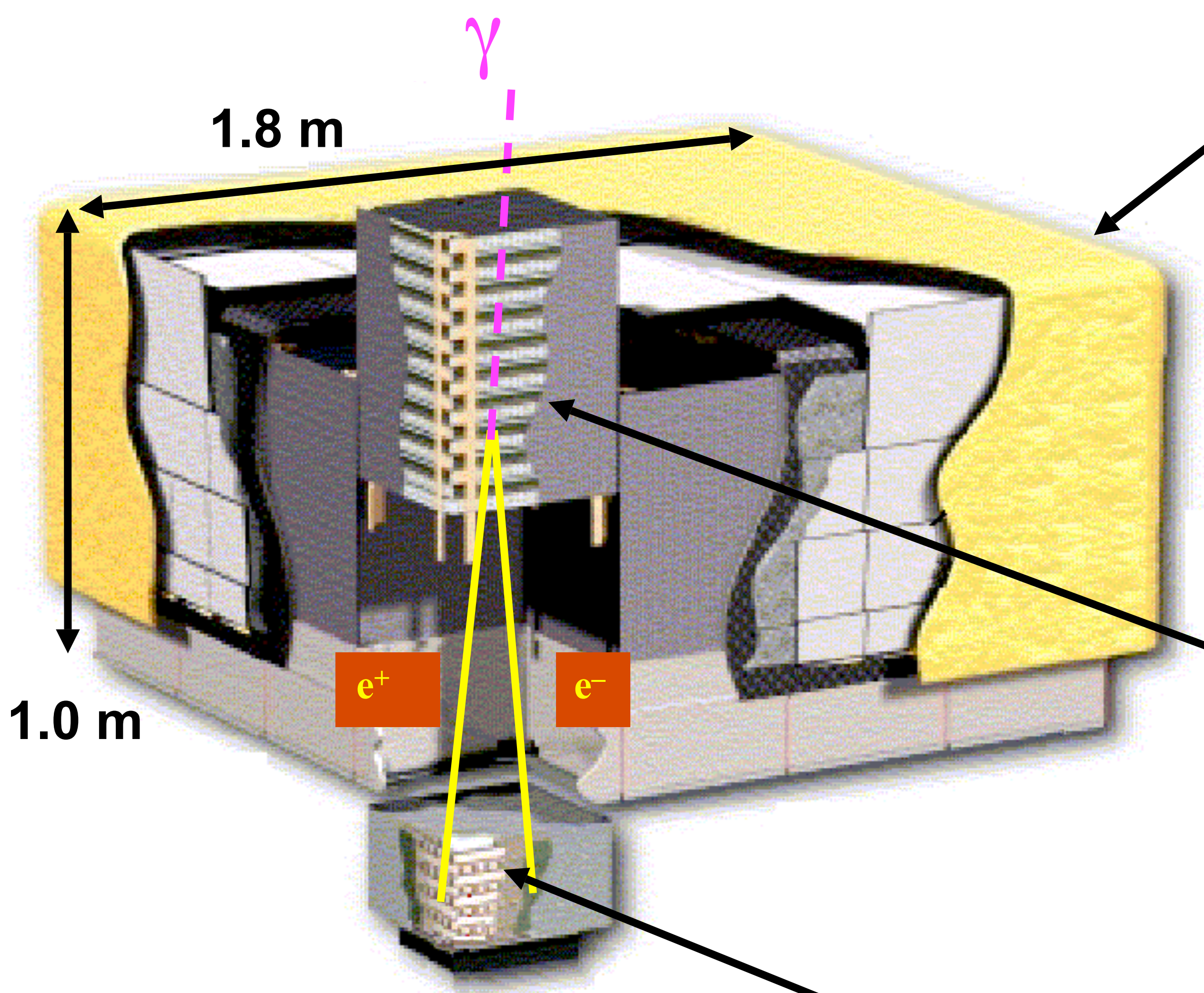


Anti-Coincidence Detector
- 4% R.L.
- 89 scintillating tiles
- efficiency (>0.9997) for MIPs

Tracking detector
- 16 tungsten foils (12x3%R.L.,4x18%R.L.)
- 18 pairs of silicon strip arrays
- 884736 strips (228 micron pitch)

Calorimeter
- 8.5 radiation lengths
- 8 layers cesium iodide logs
- 1536 logs total (1200kg)

Fermi Large Area Telescope (LAT)



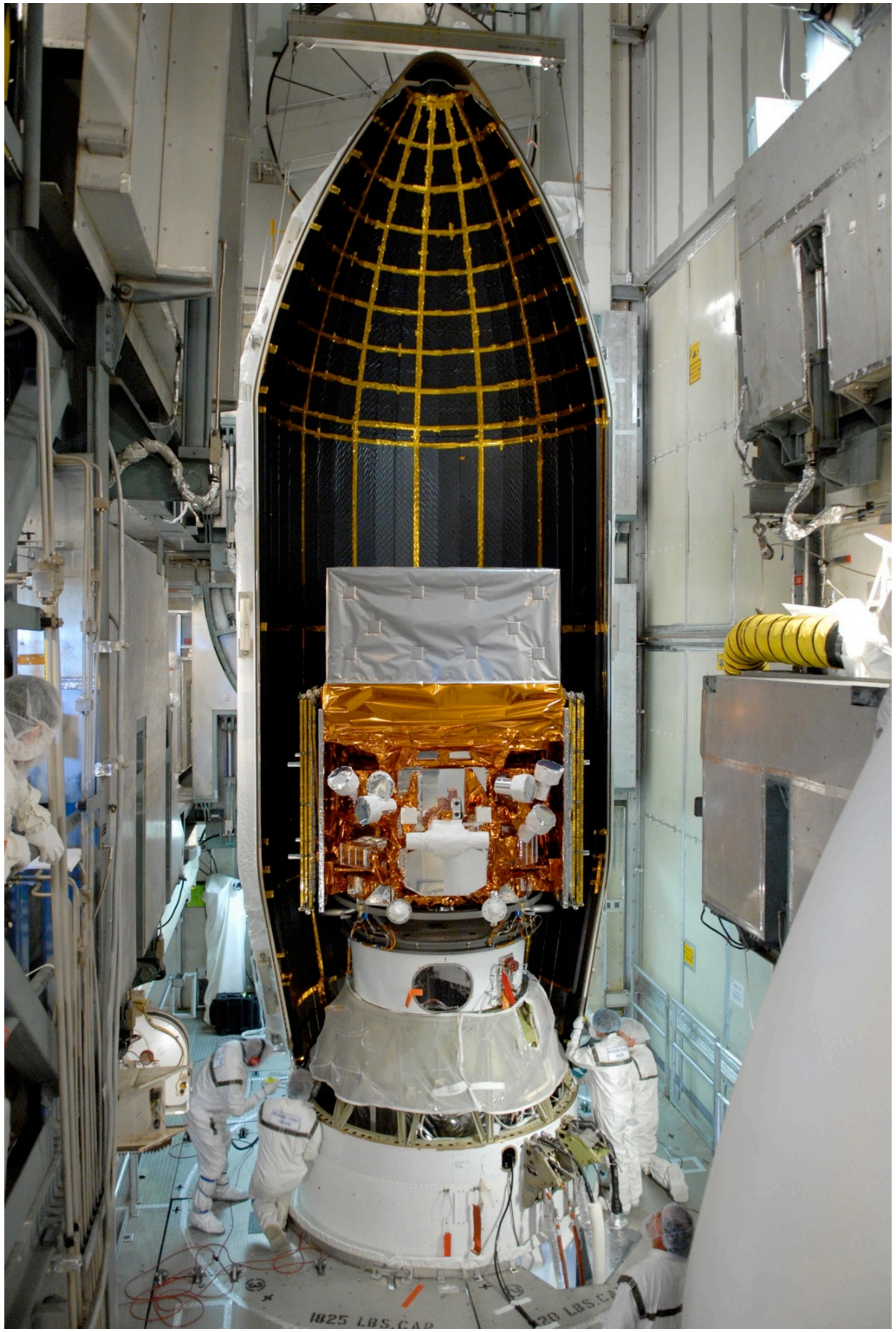
Anti-Coincidence Detector
- 4% R.L.
- 89 scintillating tiles
- efficiency (>0.9997) for MIPs

Tracking detector
- 16 tungsten foils (12x3%R.L.,4x18%R.L.)
- 18 pairs of silicon strip arrays
- 884736 strips (228 micron pitch)

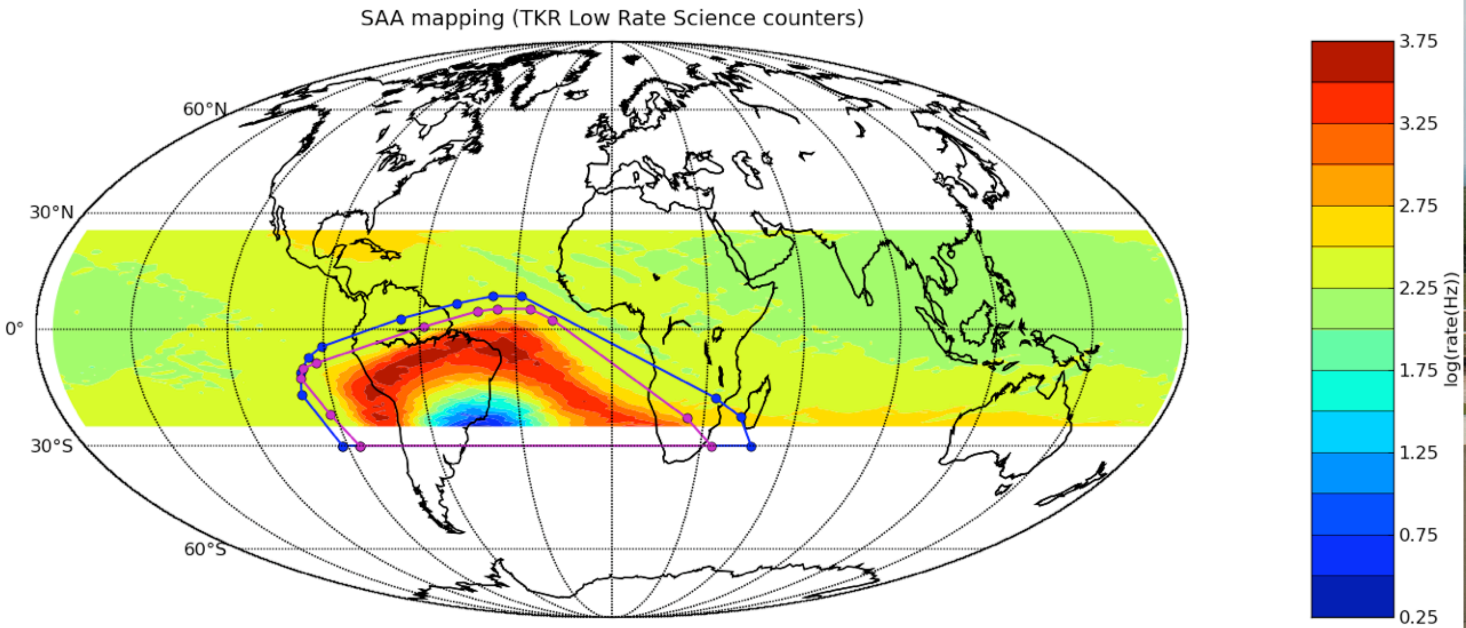
Calorimeter
- 8.5 radiation lengths
- 8 layers cesium iodide logs
- 1536 logs total (1200kg)

Trigger
- Overall HW Trigger Rate ~few KHz
- Software Filters Reduce Rate
- Downlink: ~400-500 Hz
- Rate after Ground Cuts: ~few Hz

Fermi Large Area Telescope (LAT)

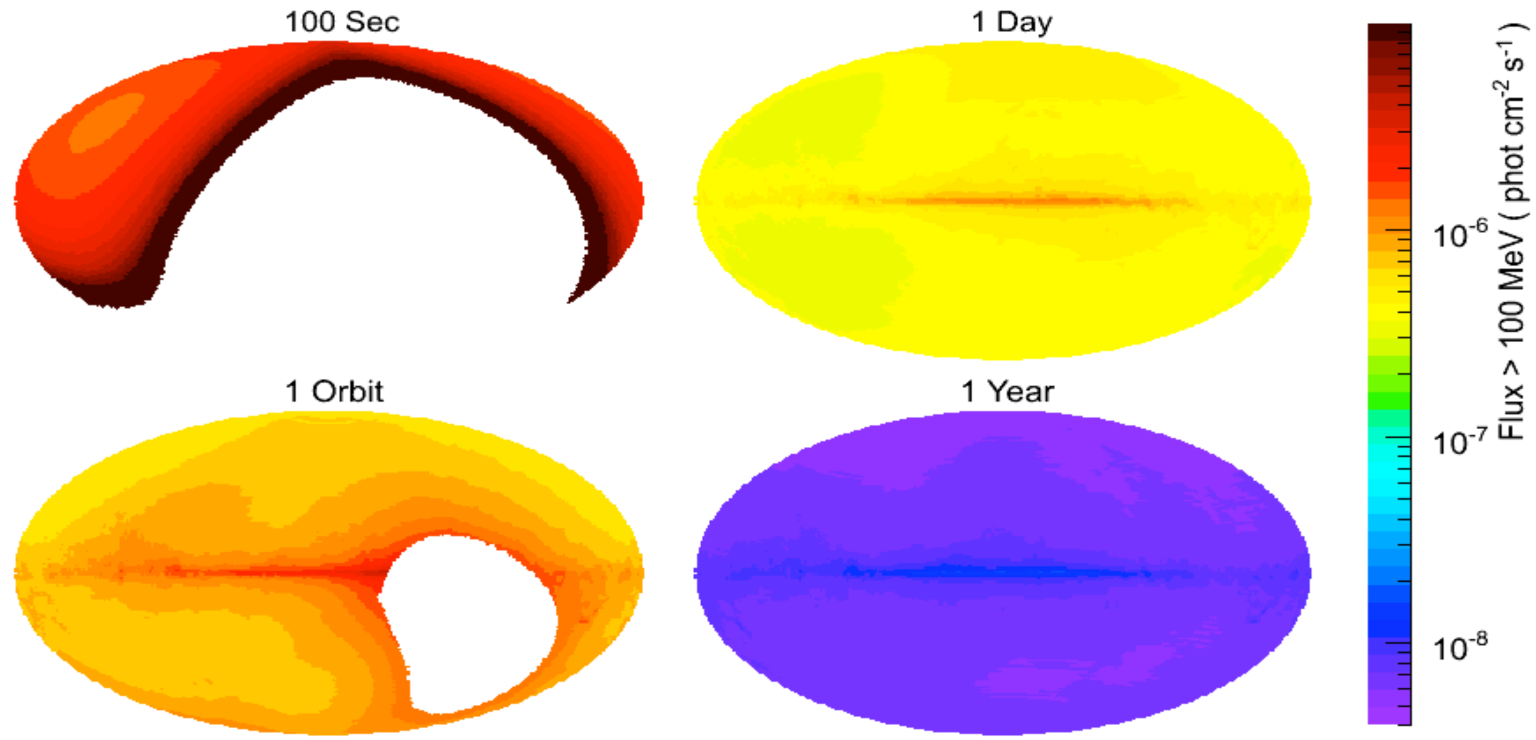


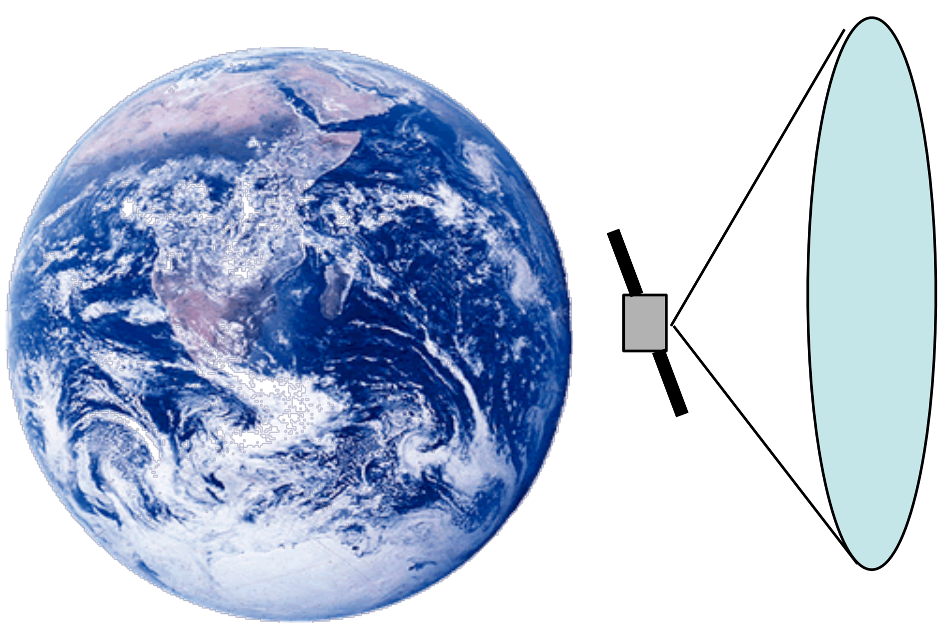
- Very Successful Launch!
- Orbit:
  - ★ Altitude: 565 km
  - ★ Inclination: 25.6 deg
  - ★ Period: ~90 min
- Turn off through SAA
- Lifetime: 5 years min.
  - ★ No expendable



Operational Modes

- Sky Survey Mode
  - ★ Typical Mode of operation
  - ★ View full sky every 2 orbits
  - ★ “Rocking” Mode (up/down)
- Targets of Opportunity
  - ★Autonomous Repoint (GRBs)
  - ★Slew to keep ToO in FOV
  - ★Later years: ToO Proposals

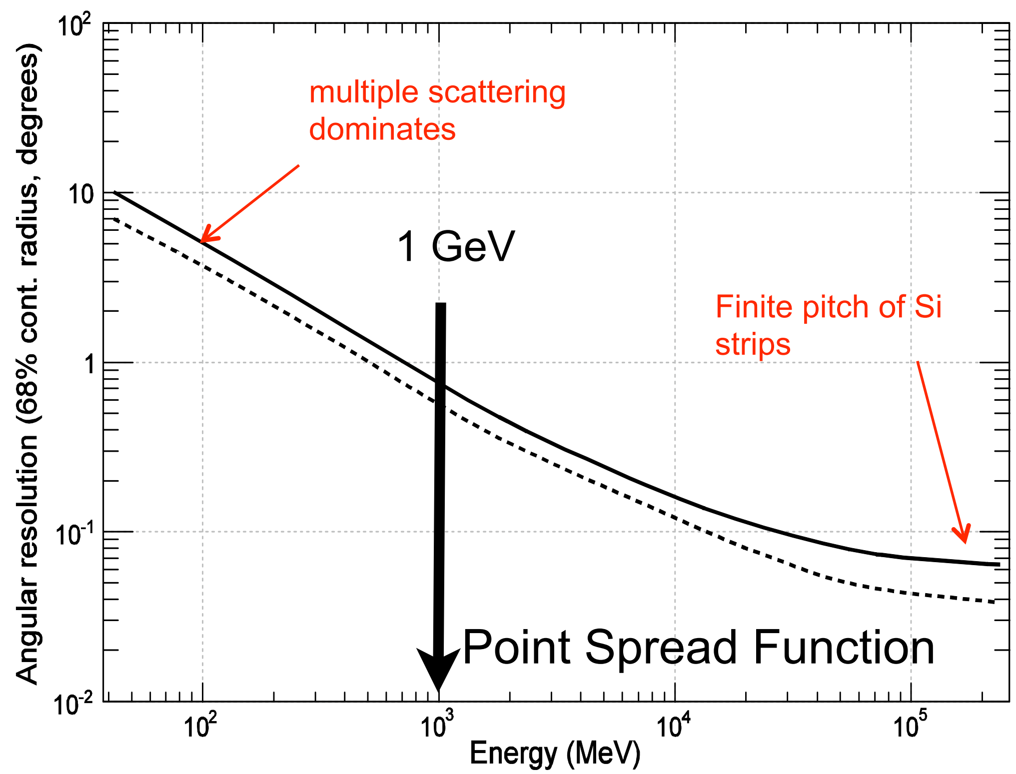


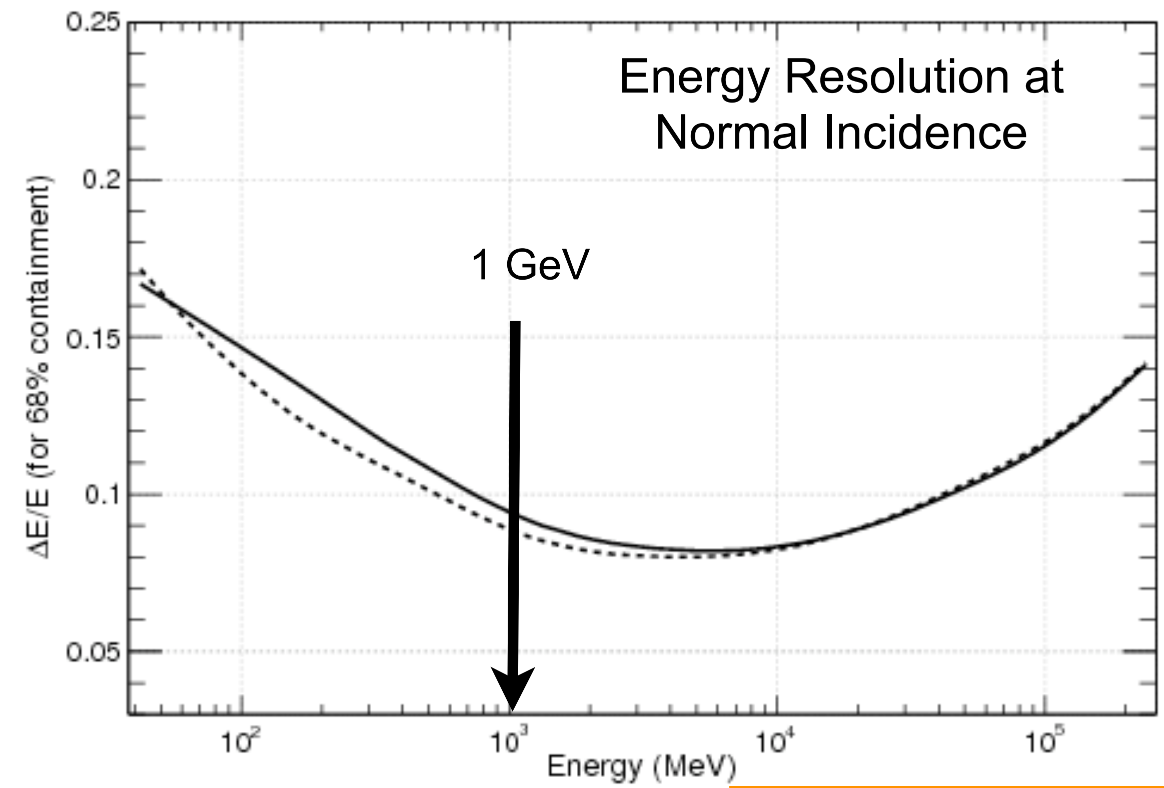


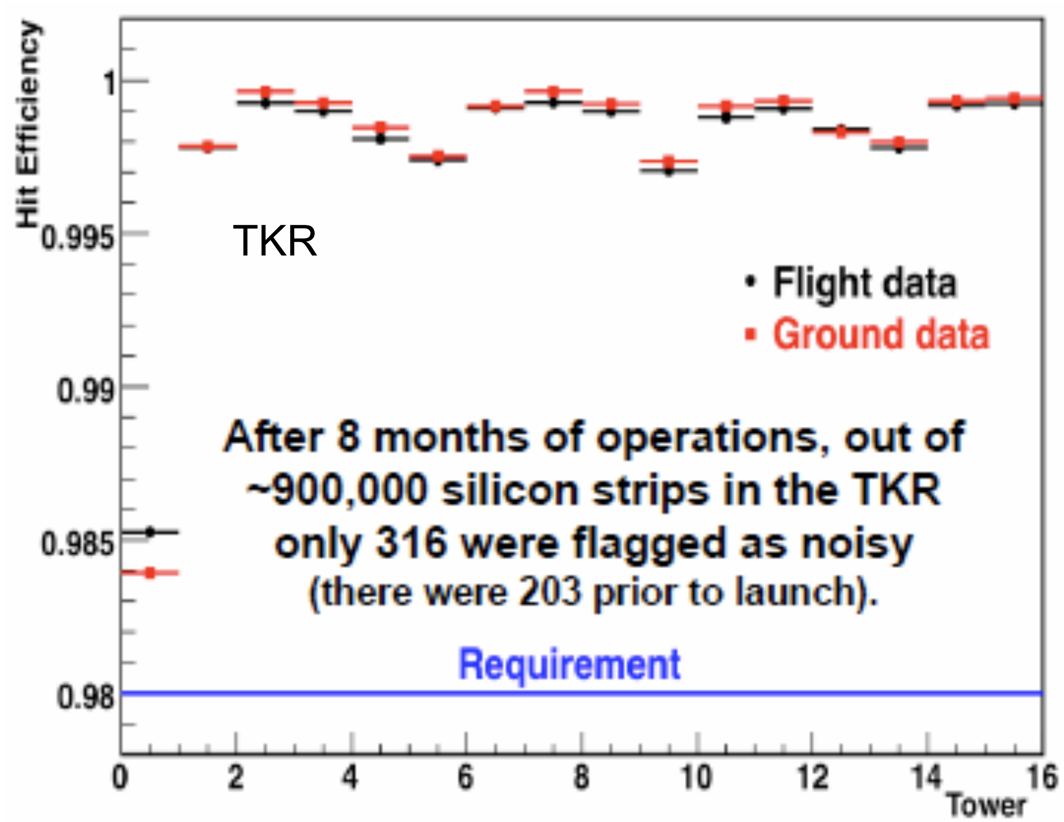
LAT: Wide Field of View ~2.4 sr

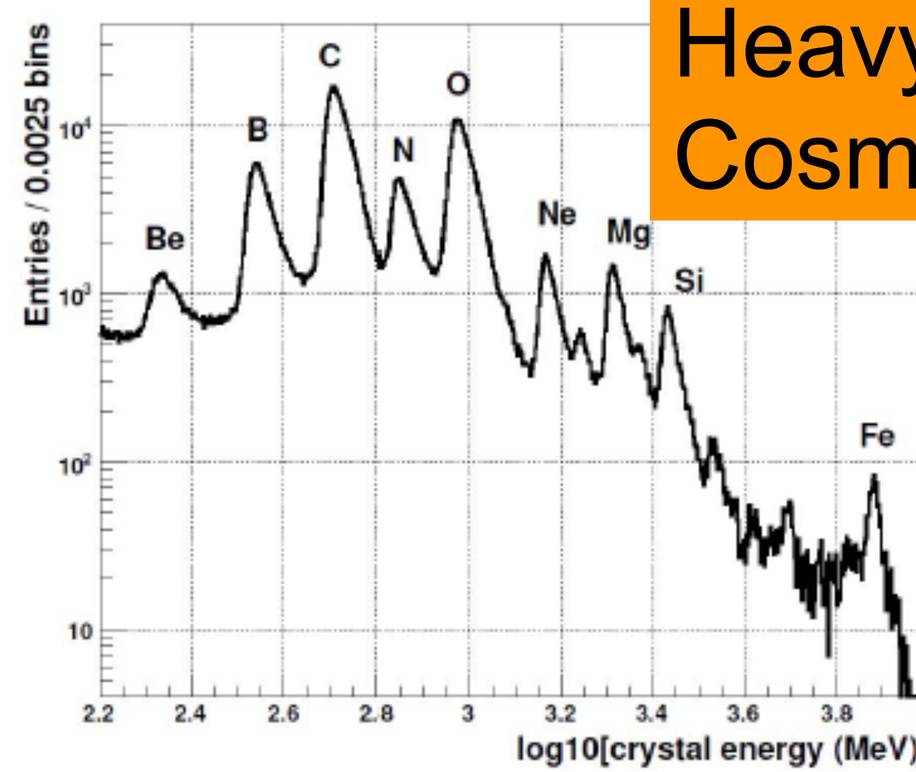
GBM: See almost all of the sky not occulted by the earth

Detector Performance





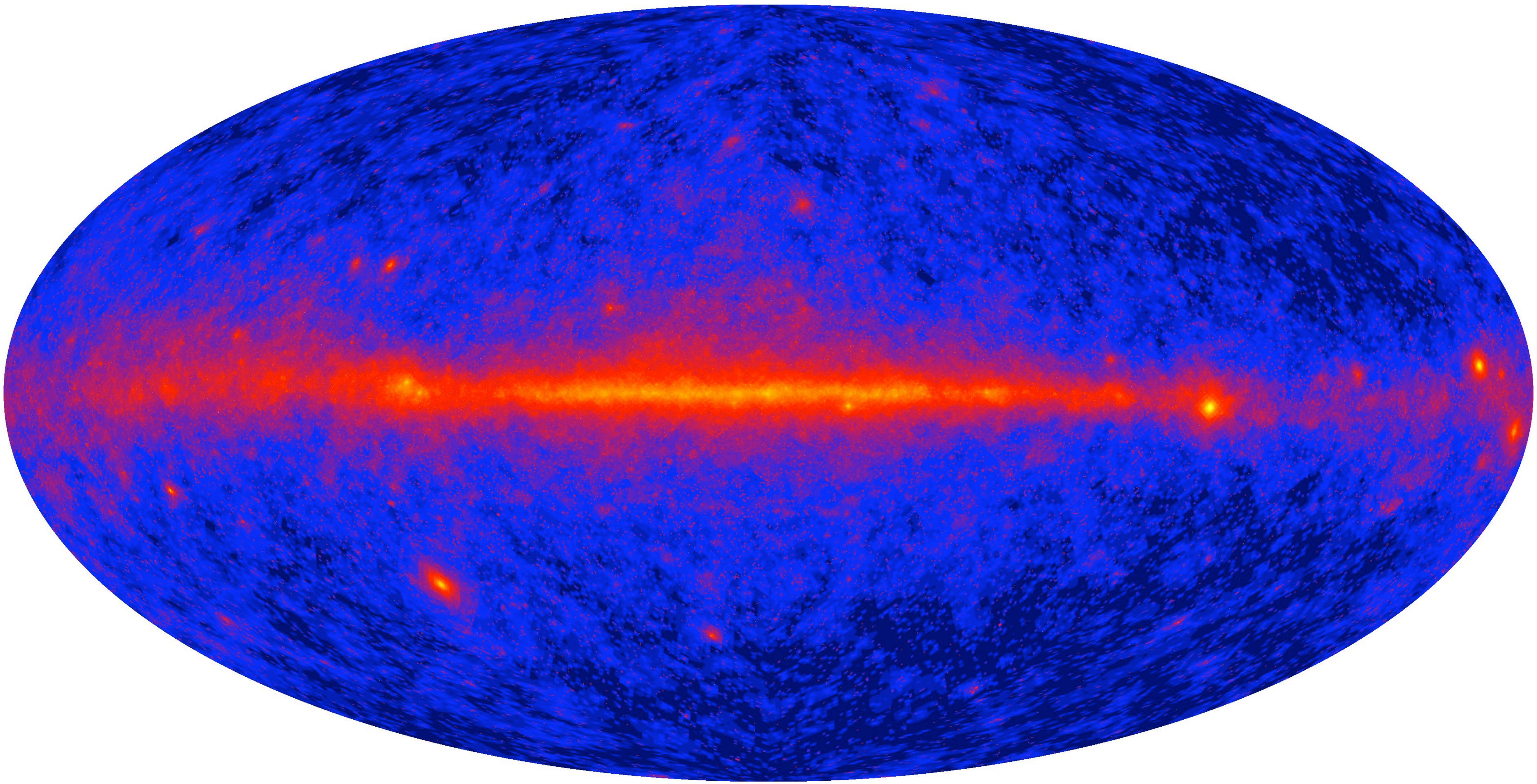




Heavy Ion Cosmic Rays!

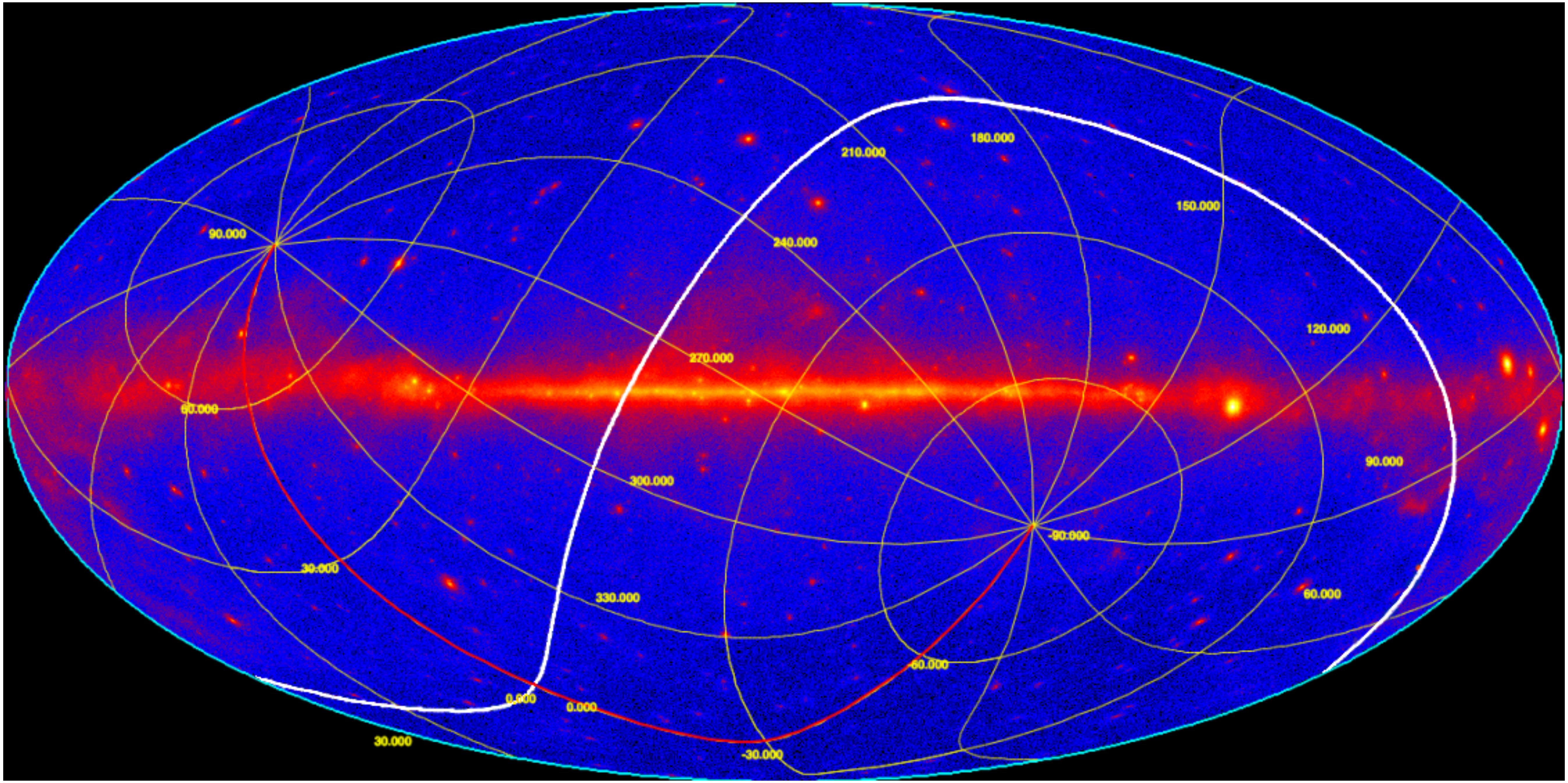
The Gamma Ray Sky

All Sky First Light Data: Few Days of Data

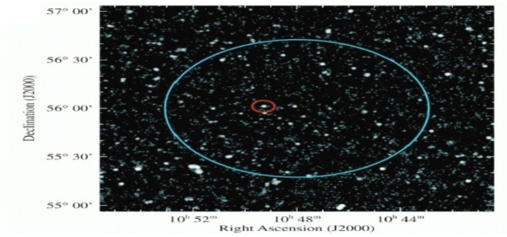


The Gamma Ray Sky

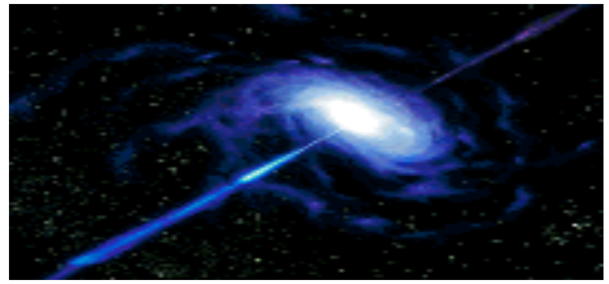
All Sky View: First Year of Data



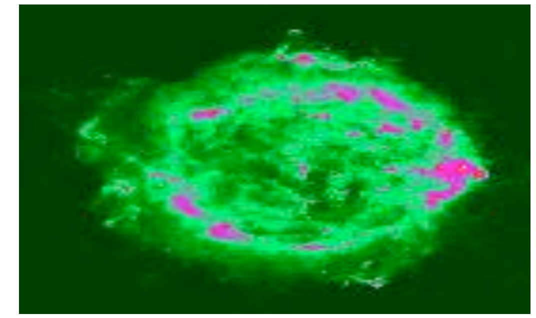
Fermi Science



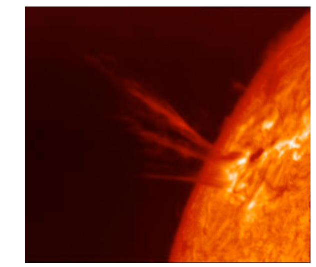
Unidentified sources



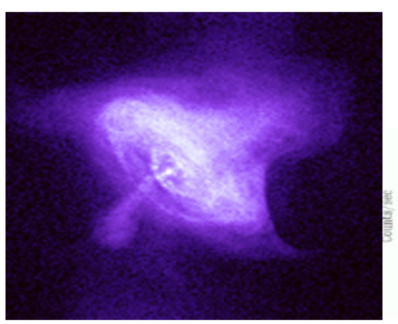
Active Galactic Nuclei



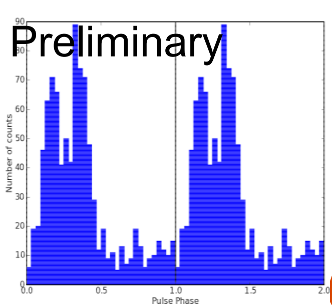
Cosmic ray acceleration

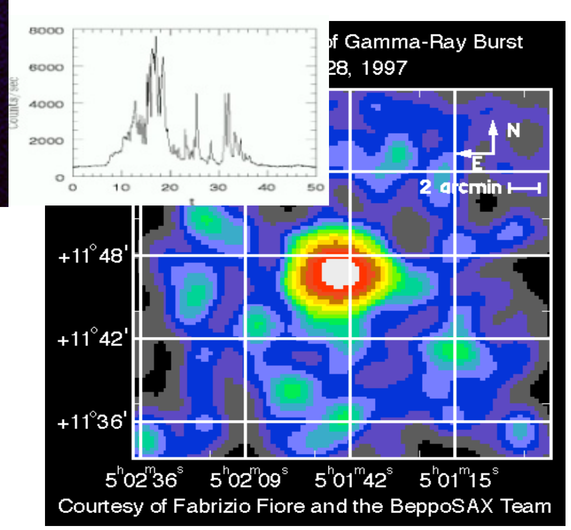


Solar flares

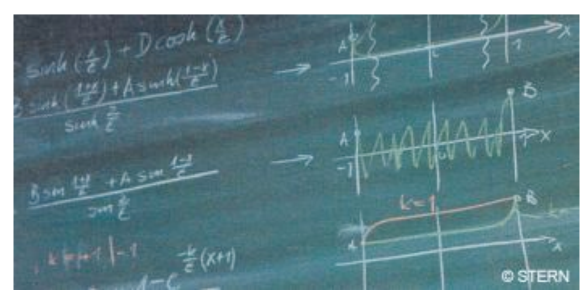


Pulsars

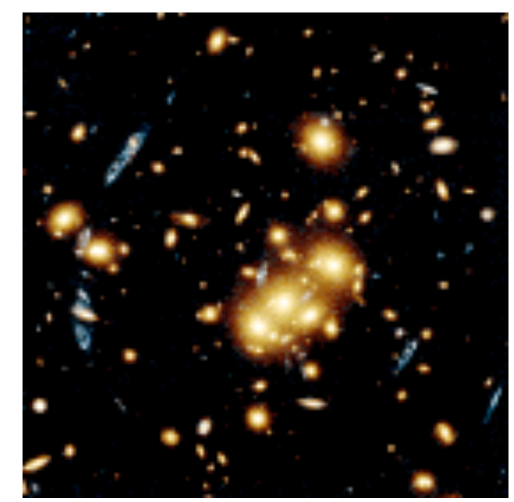




Gamma Ray Bursts



Quantum Gravity?

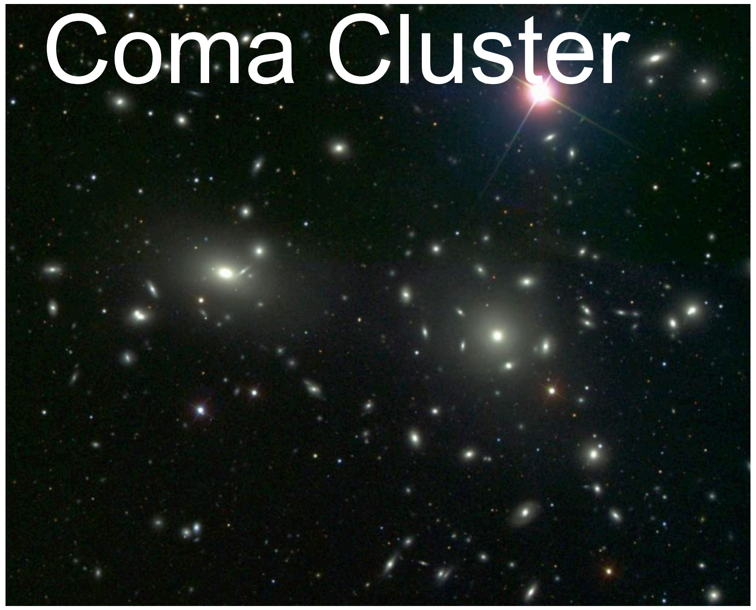


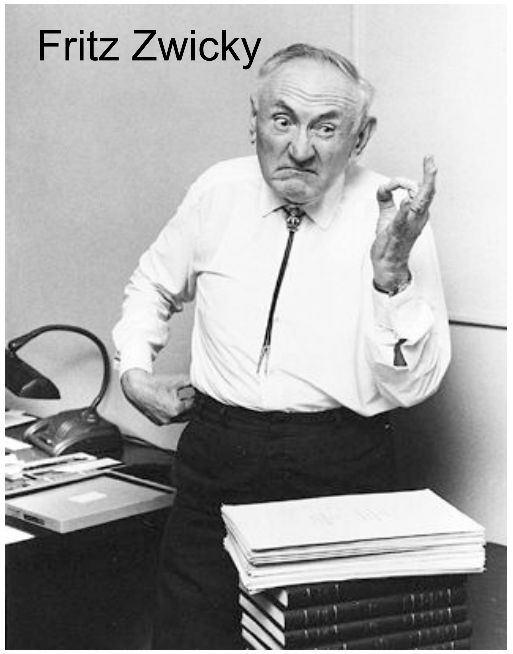
Dark matter

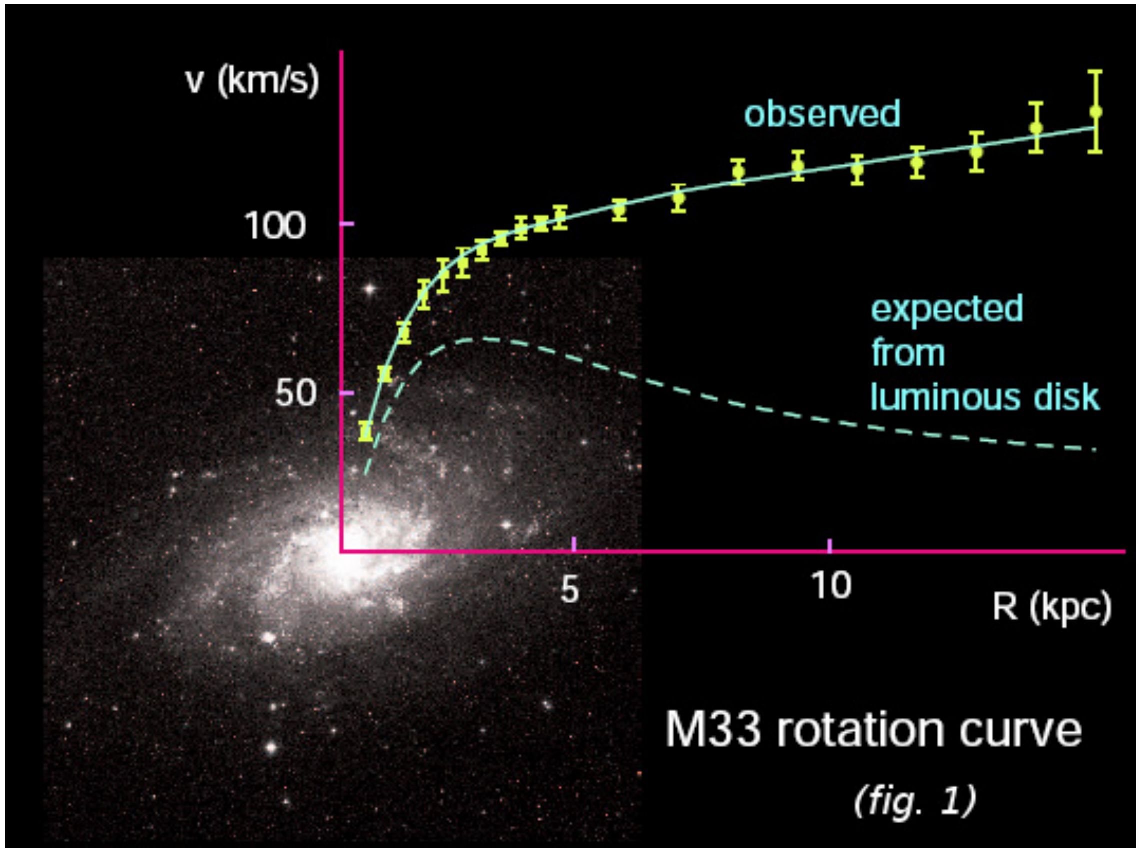
0.01 GeV | 0.1 GeV | 1 GeV | 10 GeV | 100 GeV | 1 TeV

The Dark Side...

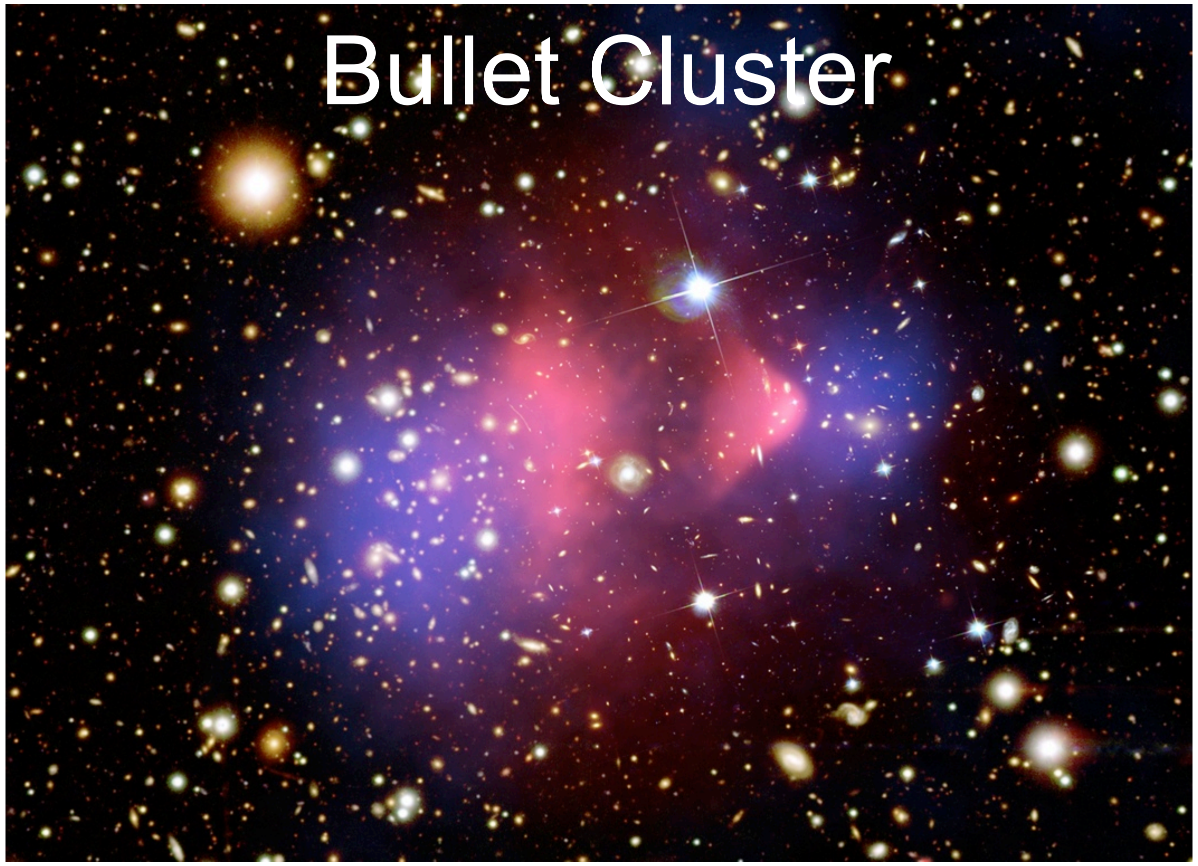
- The universe seems to be composed of ~23% dark matter.
- Candidate:
  Weakly Interacting Massive Particle
- WIMP might decay or self-annihilate
- Could lead to gamma-rays.







www4.nau.edu/



Chandra/Hubble

Spectral shape & flux magnitude

γ-ray flux factors

$\int(\sum_i dN/dE\ B_i)dE$

x

$4\pi \int\rho^2(r)r^2dr\ /\ M^2_{WIMP}$

x

$<\sigma v>\ /\ 2$

x

$1/4\pi d^2$

Energy spectrum
(depends upon particle mass, branching fractions)

x

number density^2
(depends upon dark matter clustering)

x

annihilation cross-section
(depends upon underlying particle physics, inflation…)

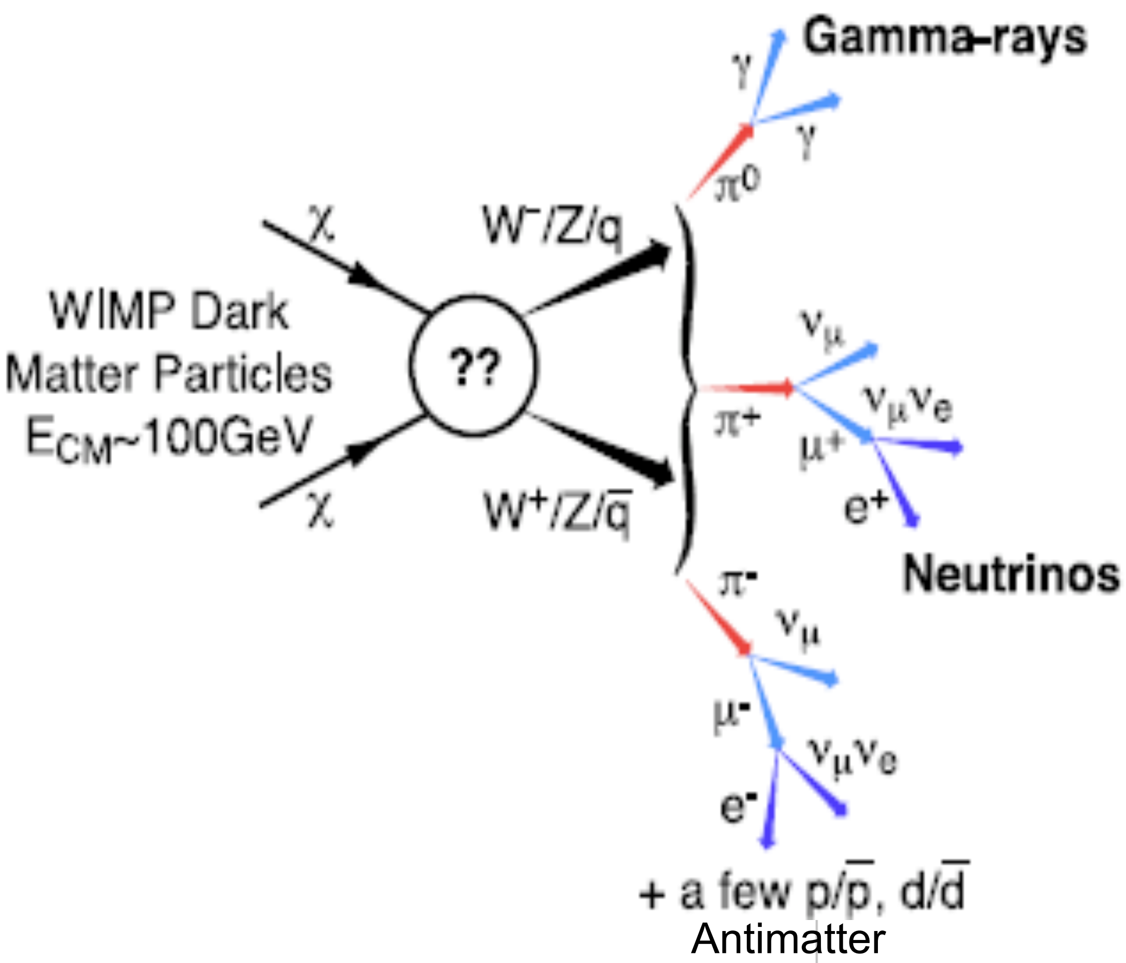
x

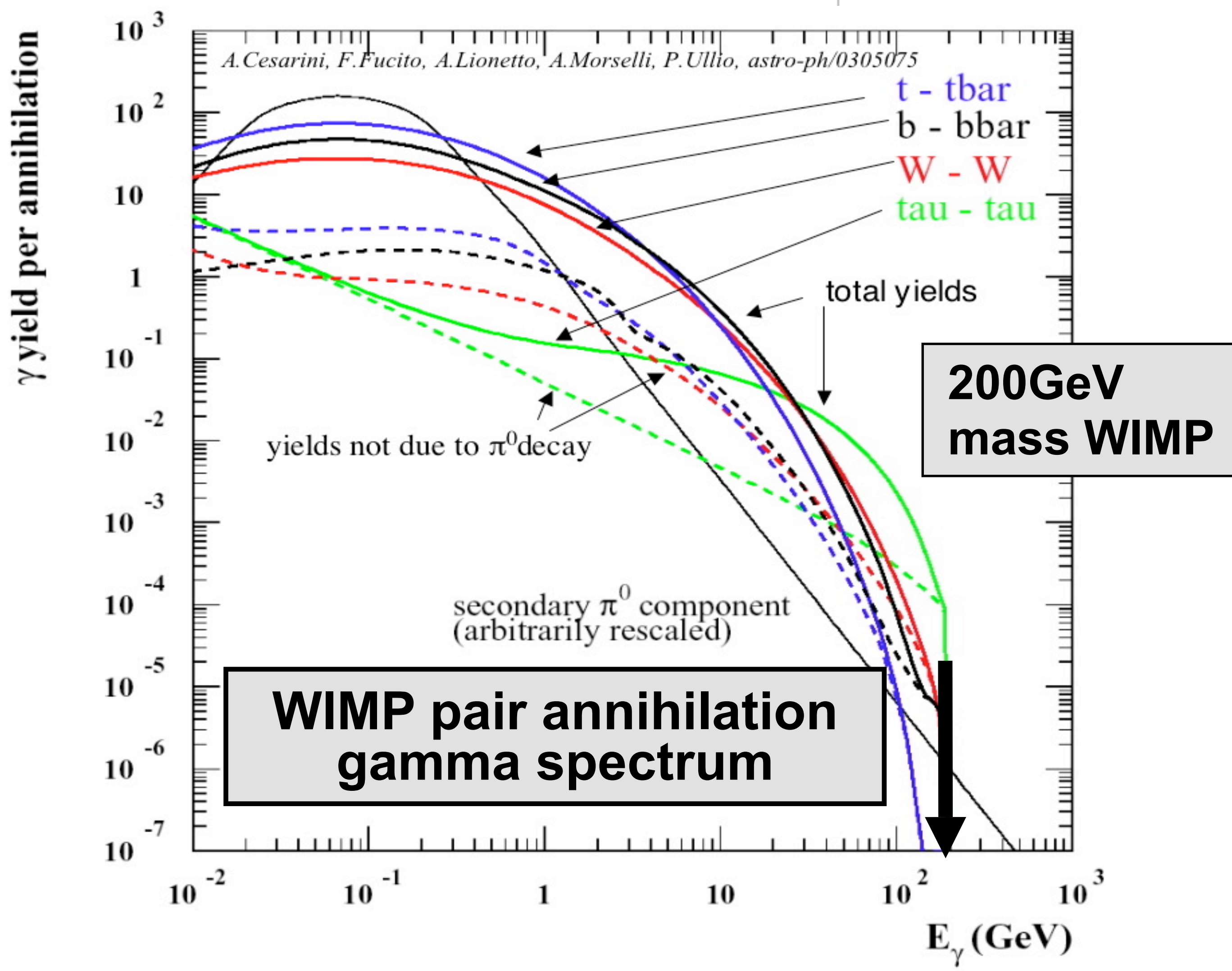
distance^{-2}
(depends upon dark matter clustering)

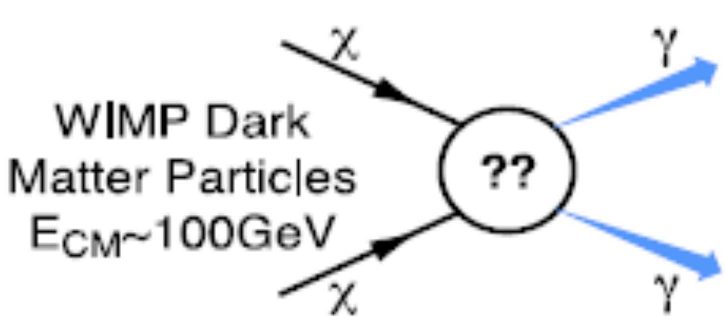
Spectral shape: Universal

Flux magnitude: Factors difficult to disentangle for single point source

WIMP Annihilation







Gamma ray yield per final state $b\bar{b}$

M_{WIMP}	Total# γ	>100MeV	>1GeV	>10GeV
10 GeV	17.3	12.6	1.0	0
100GeV	24.5	22.5	12.4	1.0
1TeV	31.0	29.3	22.4	12.3

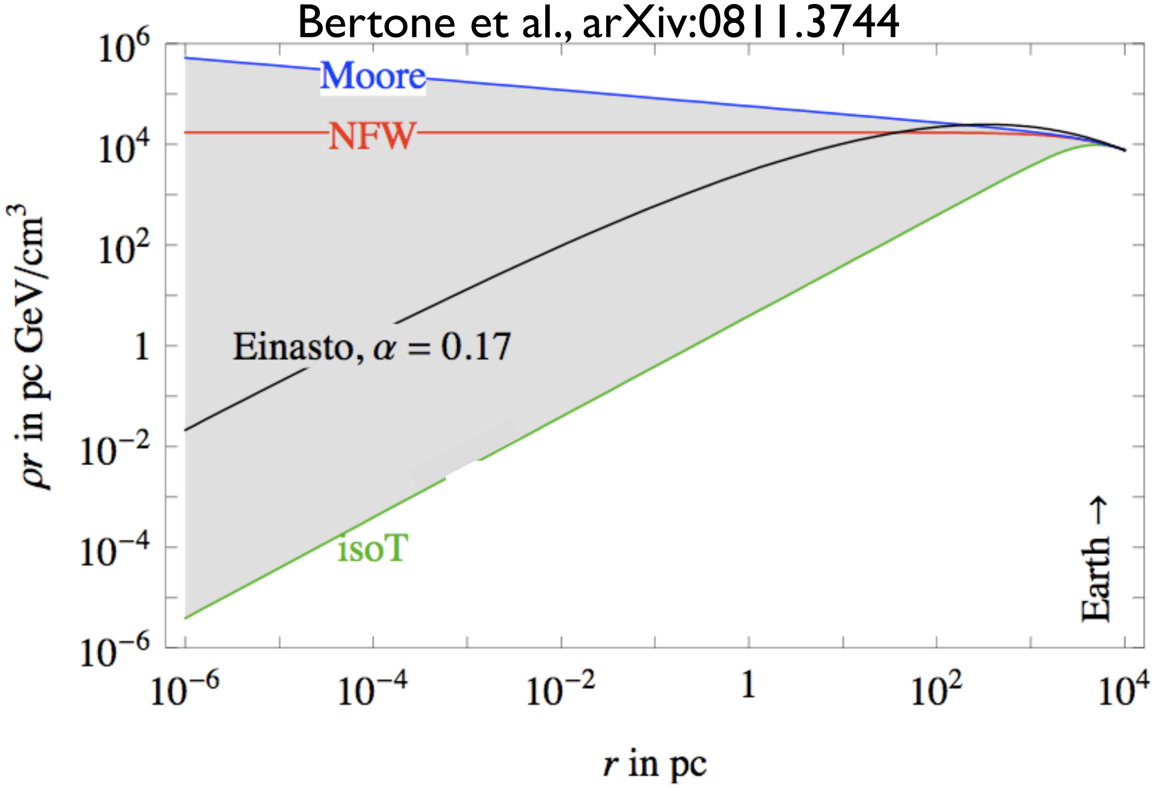
DM Distribution

- Expect concentration of DM at Galactic center.
- Significant variation in predicted behavior near the Galactic Center.
- “Traditional” Profiles (e.g. NFW) have a smooth distribution
- N-Body simulations indicate considerable clumpiness and can lead to significant boost factors.

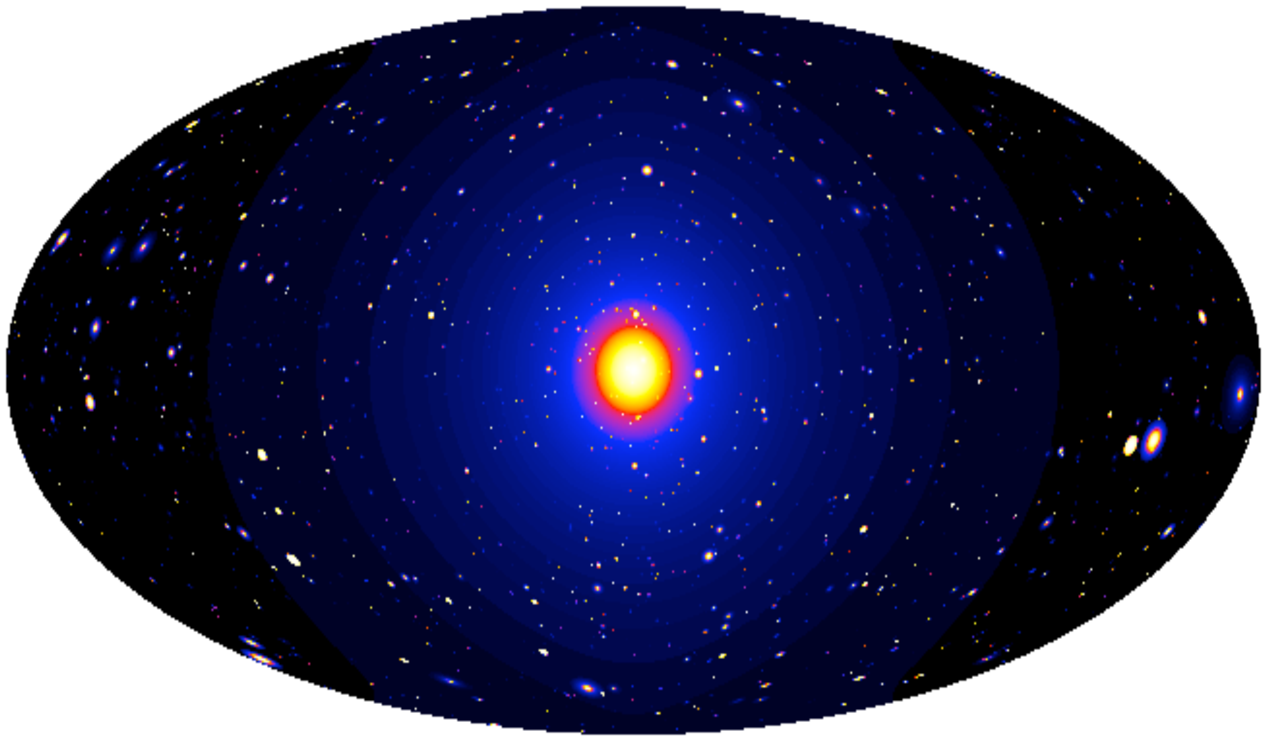
$$\rho(r)_{NFW} = \rho_0 \frac{r_0}{r} \frac{1+(r_0/a_0)^2}{1+(r/a_0)^2}$$

$$\rho_0 = 0.3 \ \ \mathrm{GeV/cm^3}$$
$$a_0 = 8.5 \ \mathrm{kpc}$$

Bertone et al., arXiv:0811.3744



Simulated Emission solely from DM Annihilations



Milky Way Halo simulated by Taylor & Babul (2005)

All-sky map of DM gamma ray emission (Baltz 2006)

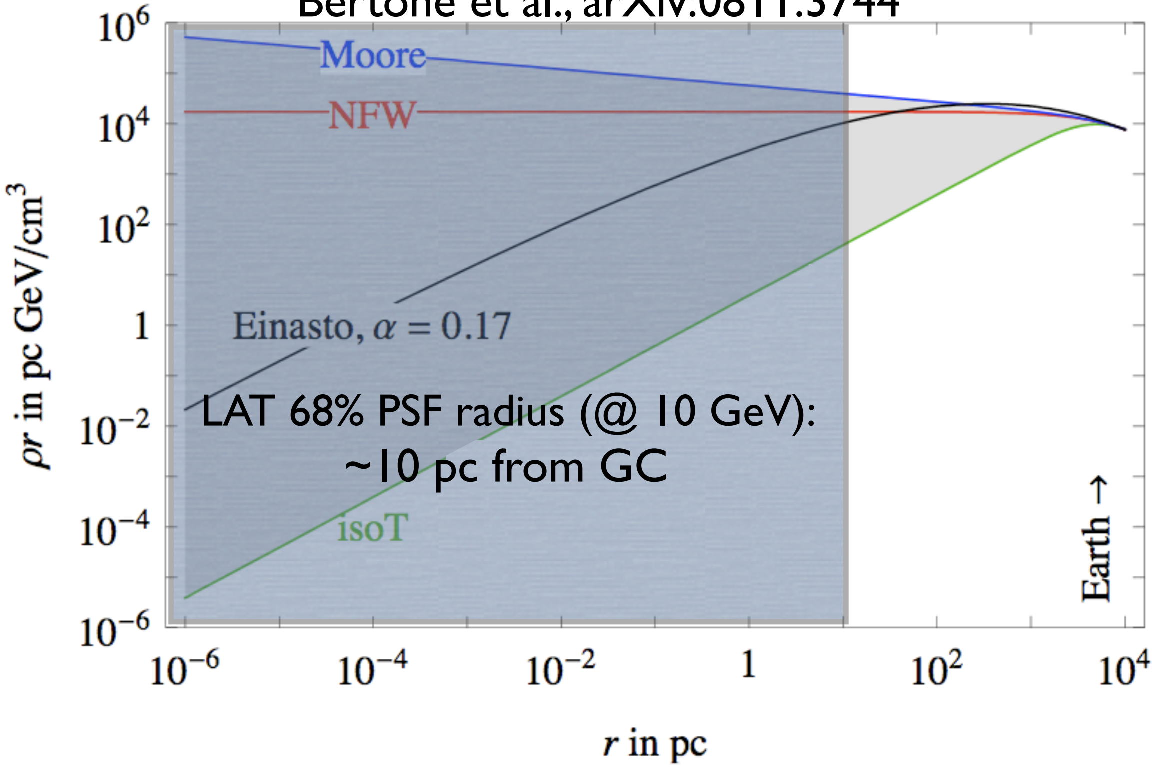
DM Distribution

- Expect concentration of DM at Galactic center.
- Significant variation in predicted behavior near the Galactic Center.
- “Traditional” Profiles (e.g. NFW) have a smooth distribution
- N-Body simulations indicate considerable clumpiness and can lead to significant boost factors.

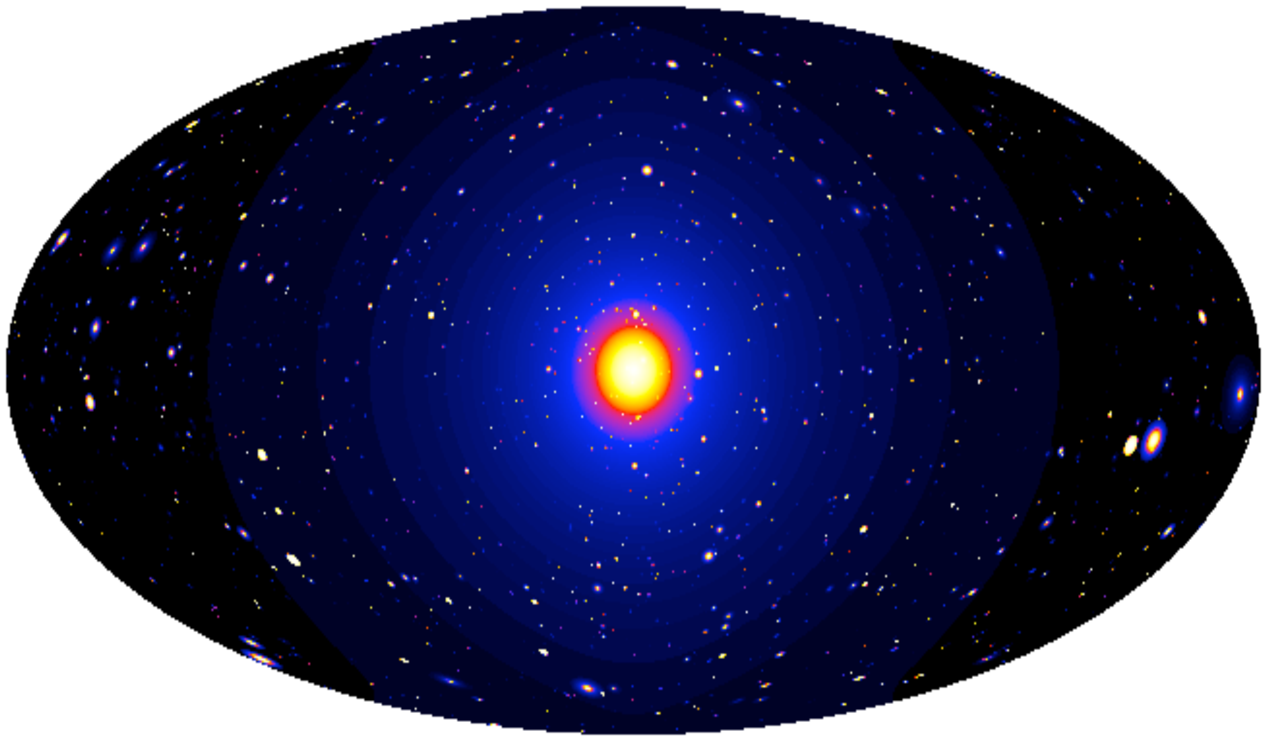
$$\rho(r)_{NFW} = \rho_0 \frac{r_0}{r} \frac{1 + (r_0/a_0)^2}{1 + (r/a_0)^2}$$

$$\rho_0 = 0.3 \ \ \mathrm{GeV/cm^3}$$
$$a_0 = 8.5 \ \mathrm{kpc}$$

Bertone et al., arXiv:0811.3744



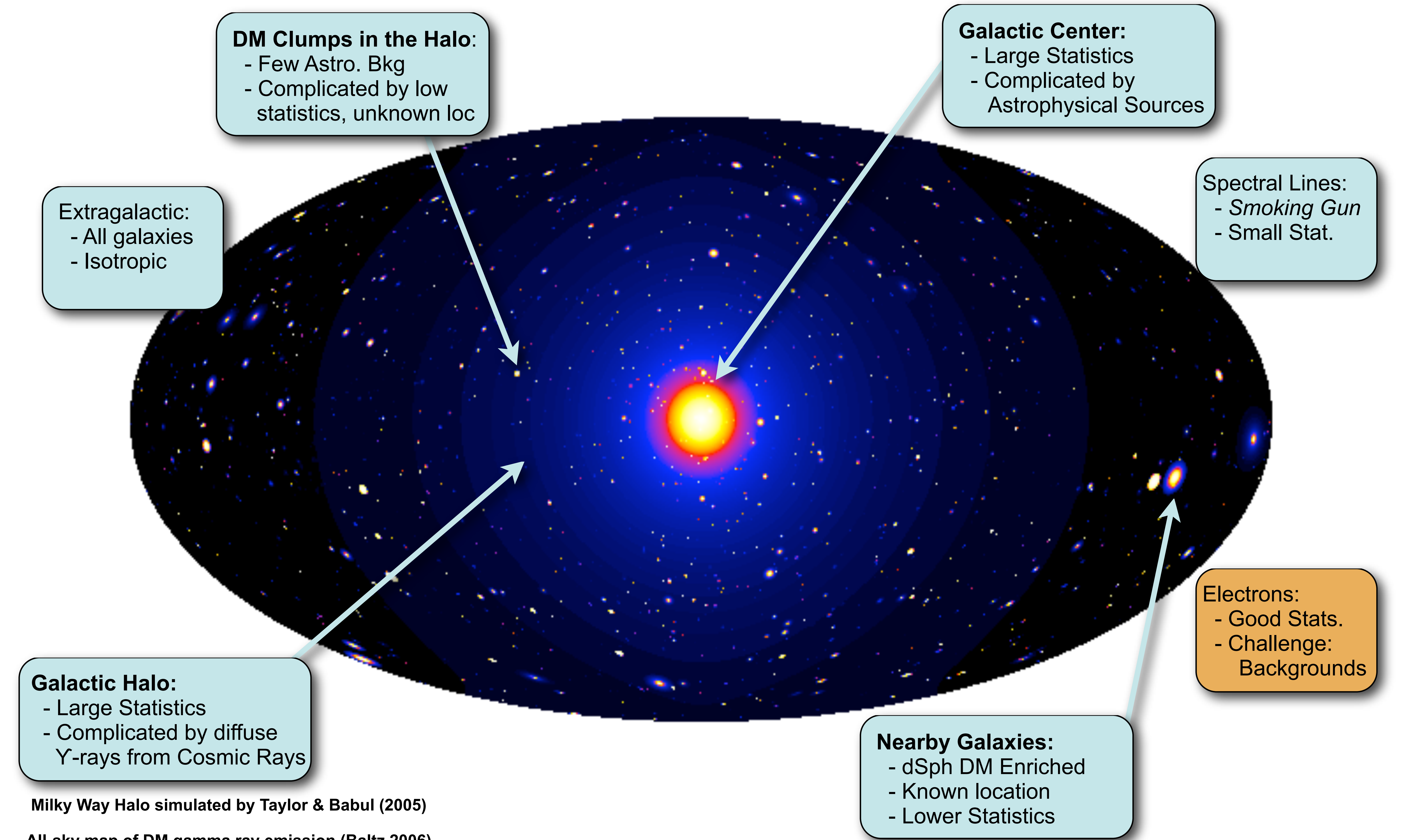
Simulated Emission solely from DM Annihilations



Milky Way Halo simulated by Taylor & Babul (2005)

All-sky map of DM gamma ray emission (Baltz 2006)

Targets in the DM Sky

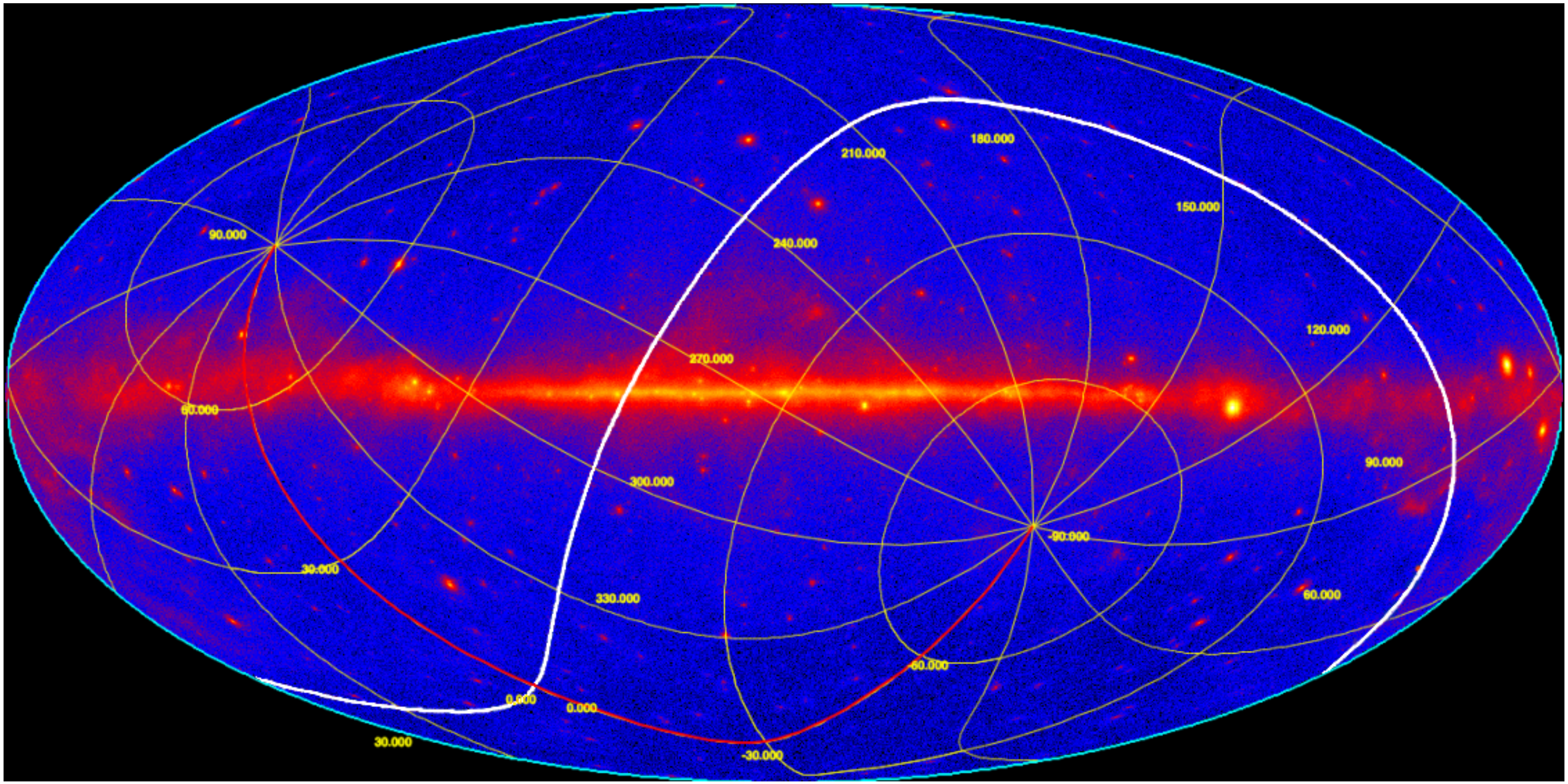


Milky Way Halo simulated by Taylor & Babul (2005)

All-sky map of DM gamma ray emission (Baltz 2006)

The Full Gamma-Ray Sky

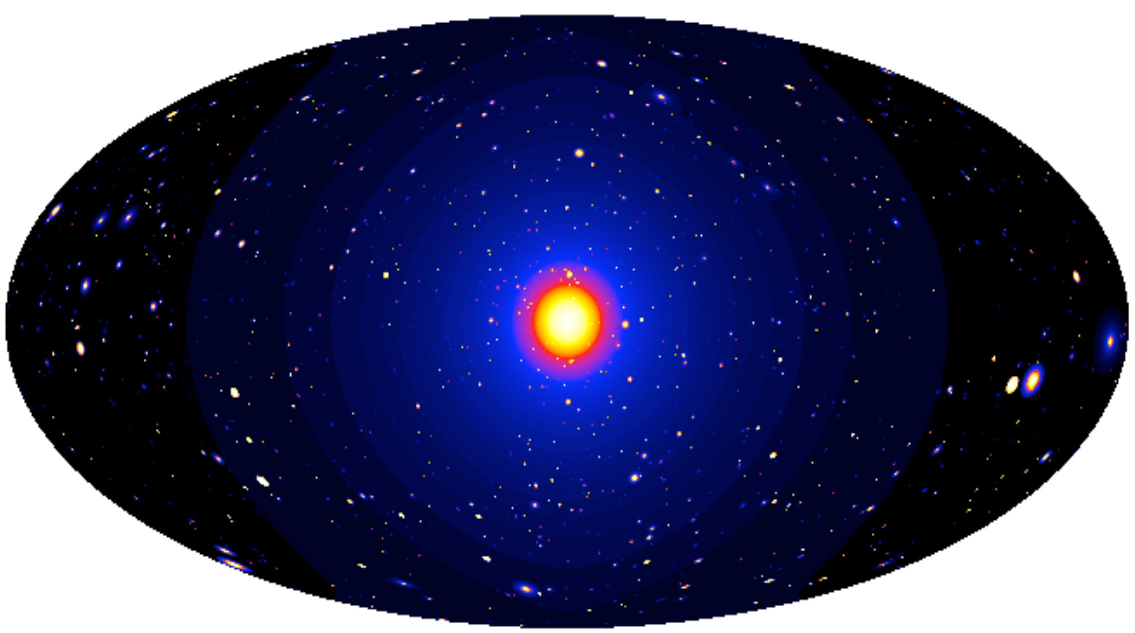
All Sky View: First Year Data

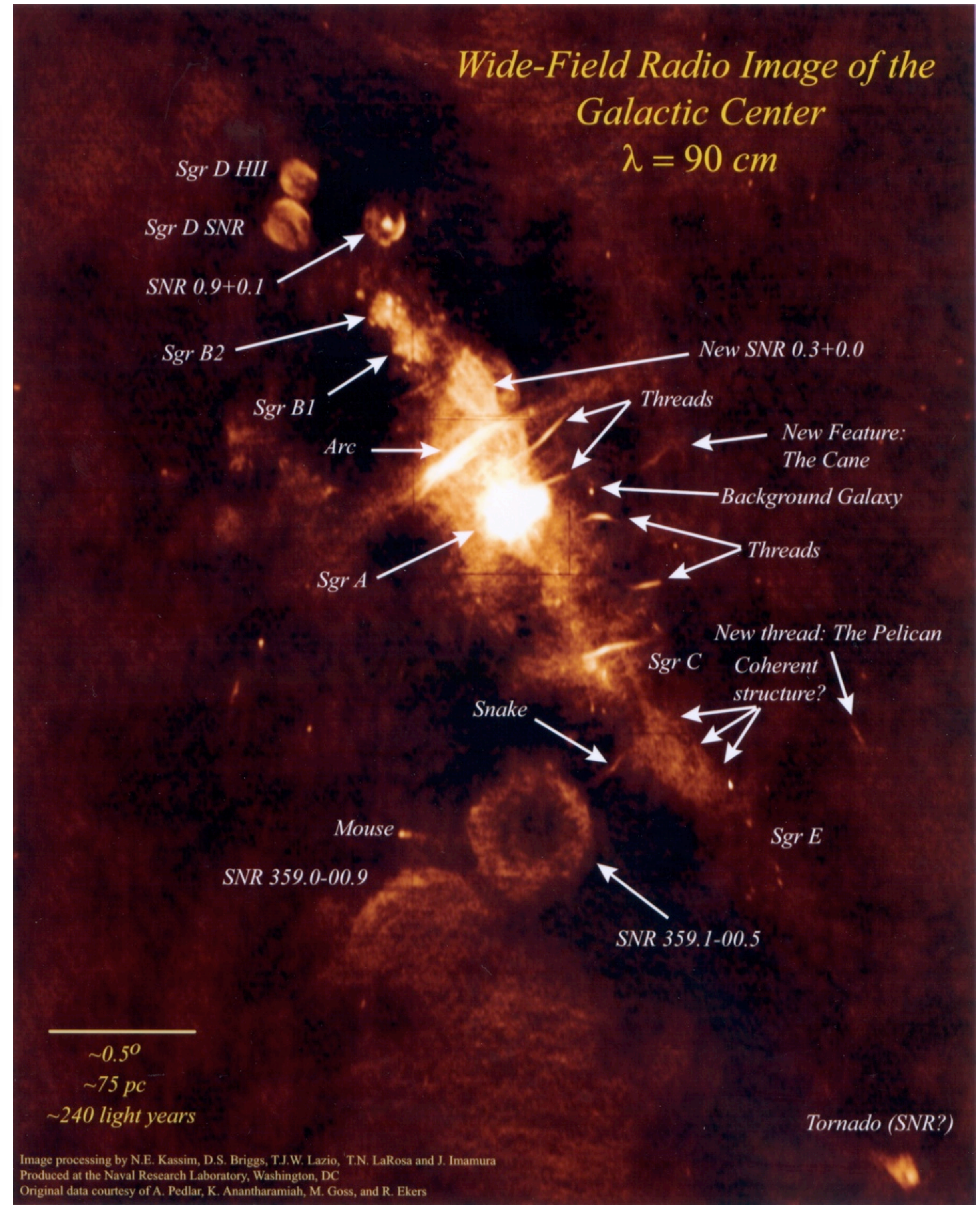


Challenge: Need to account for all the gamma-rays from non-DM sources

Galactic Center

- Highest Flux of γ-rays from DM
- Challenge: Understand Astrophysical Bkgs
  - ⋆ Source confusion
  - ⋆ Energetic Sources
  - ⋆ Diffuse Emission along line of sight.

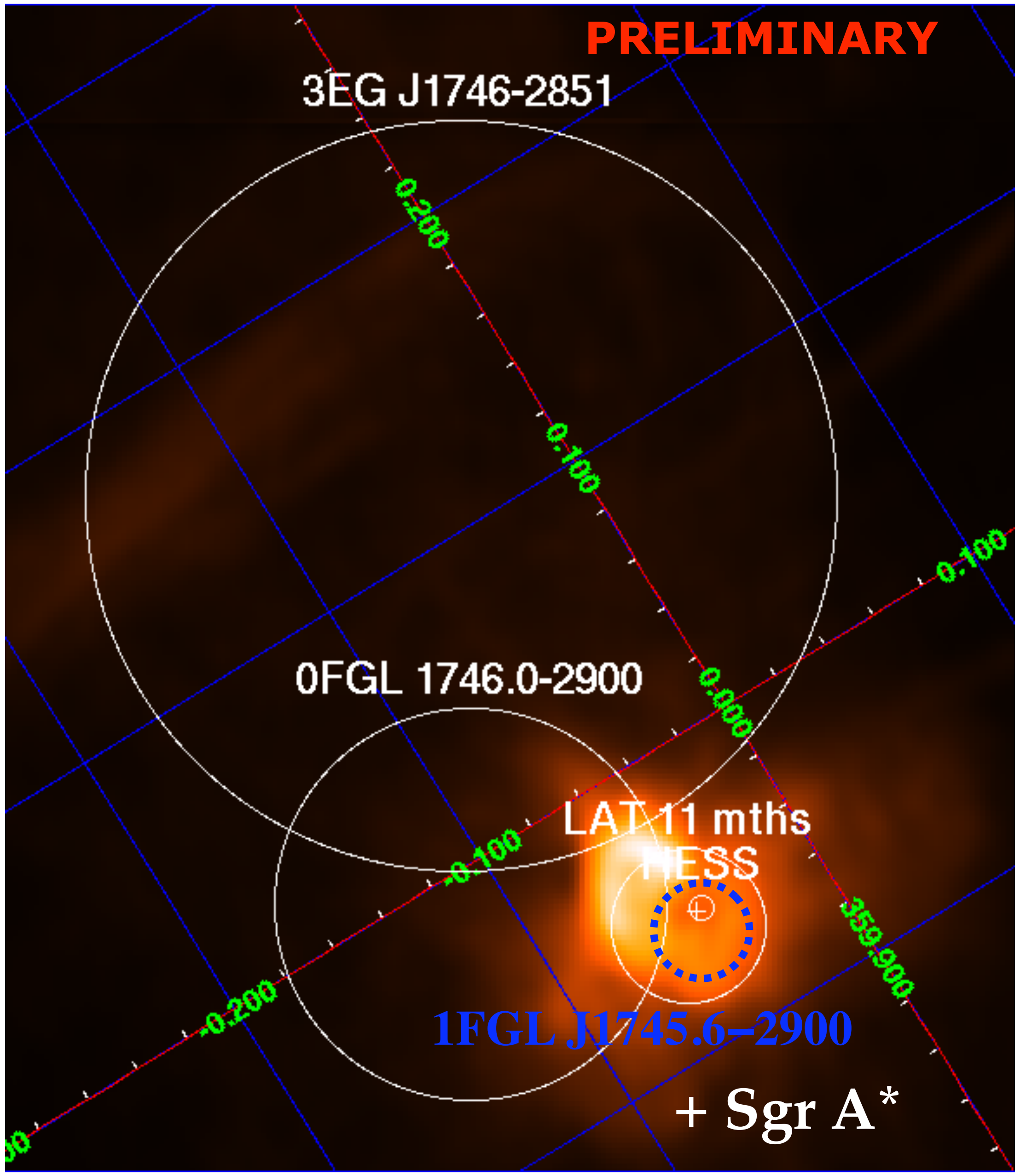




Galactic Center

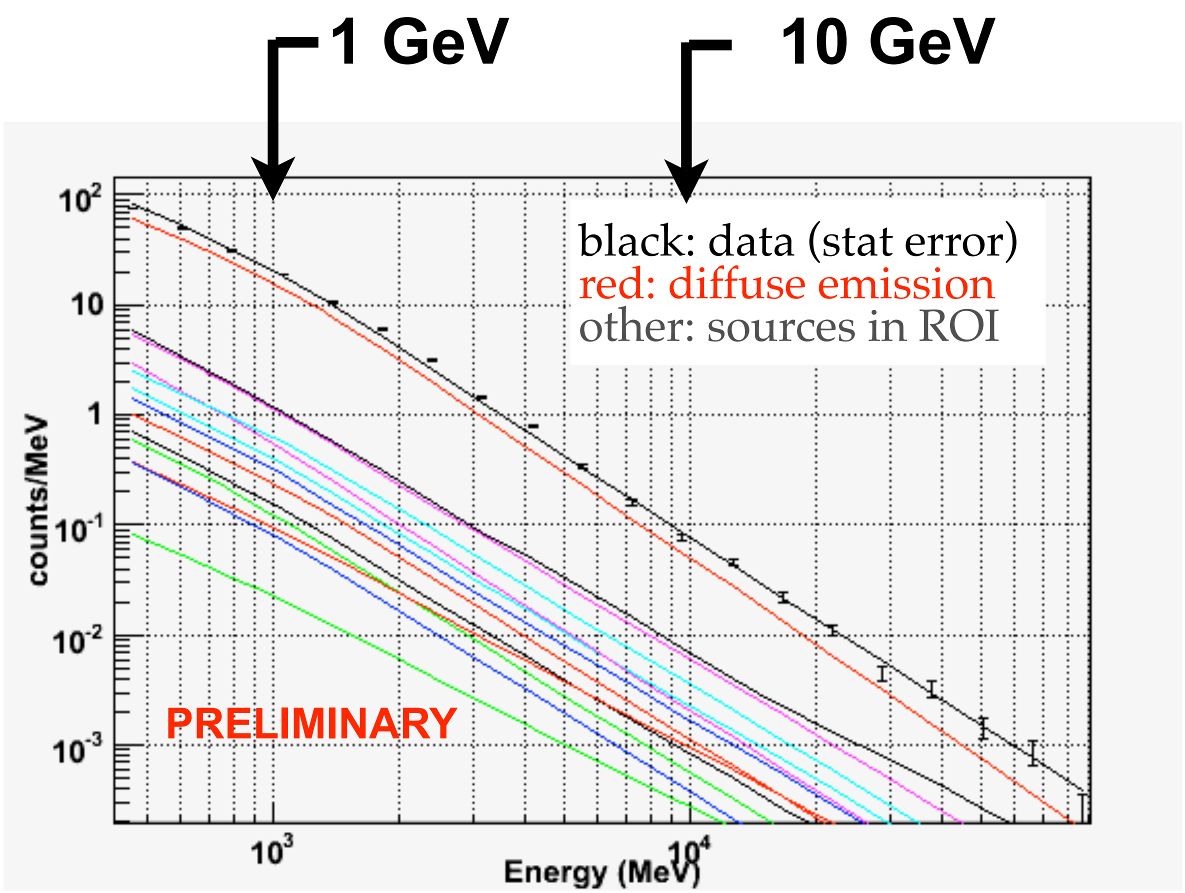
- Fermi's year 1 catalog source closest to GC
  - 1FGL J1745.6-2900
  - l = 359.941; b=-0.051
  - 95% Confinement radius 1.1'
- 25 Formal Associations based on position
  - (1 pulsar wind nebula, 1 supernova remnant, 2 TeV sources, 4 low-mass X-ray binaries, etc.)
- Future analysis based on spectral and timing information may narrow possibilities.

La Rosa et al 90 cm radio map



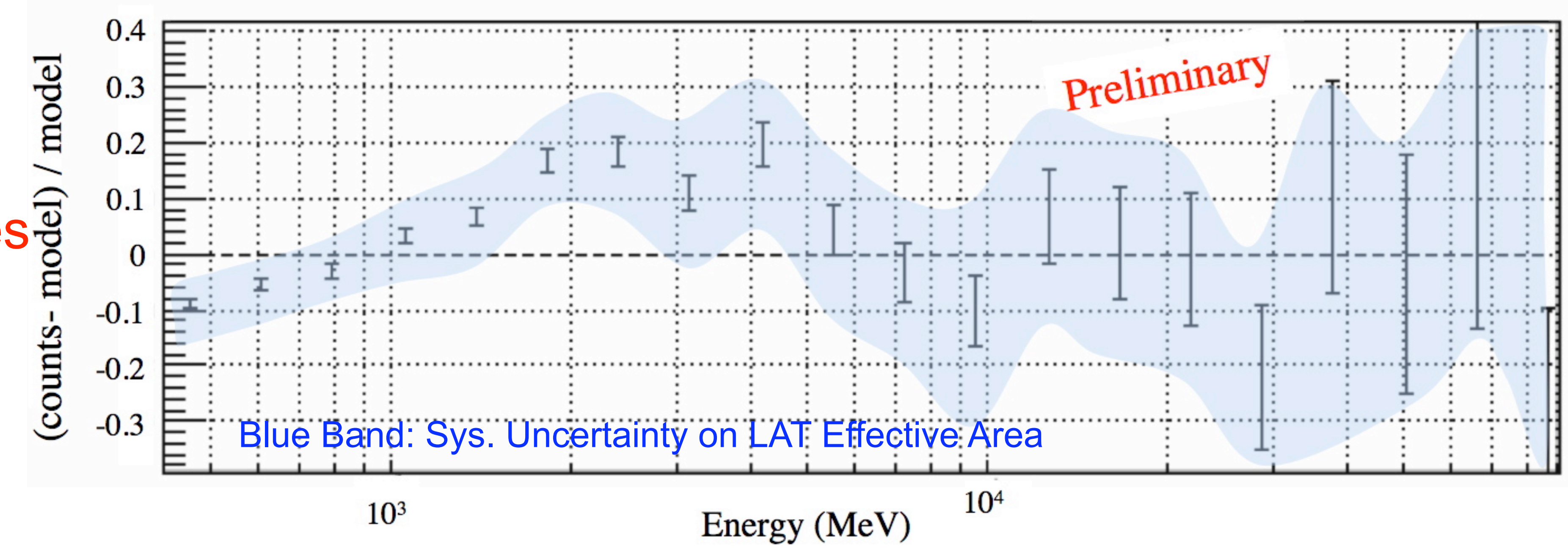
Galactic Center - DM Search

- Analysis Approach: (arXiv 0912.3828)
  - ⋆ 7 x 7 region around GC
  - ⋆ 11 months of data (front converting)
  - ⋆ E>400 MeV
- ⋆ Background Models
  - ⋆ Diffuse Emission: (GALPROP)
  - ⋆ Isotropic
  - ⋆ Point Sources: 1FGL

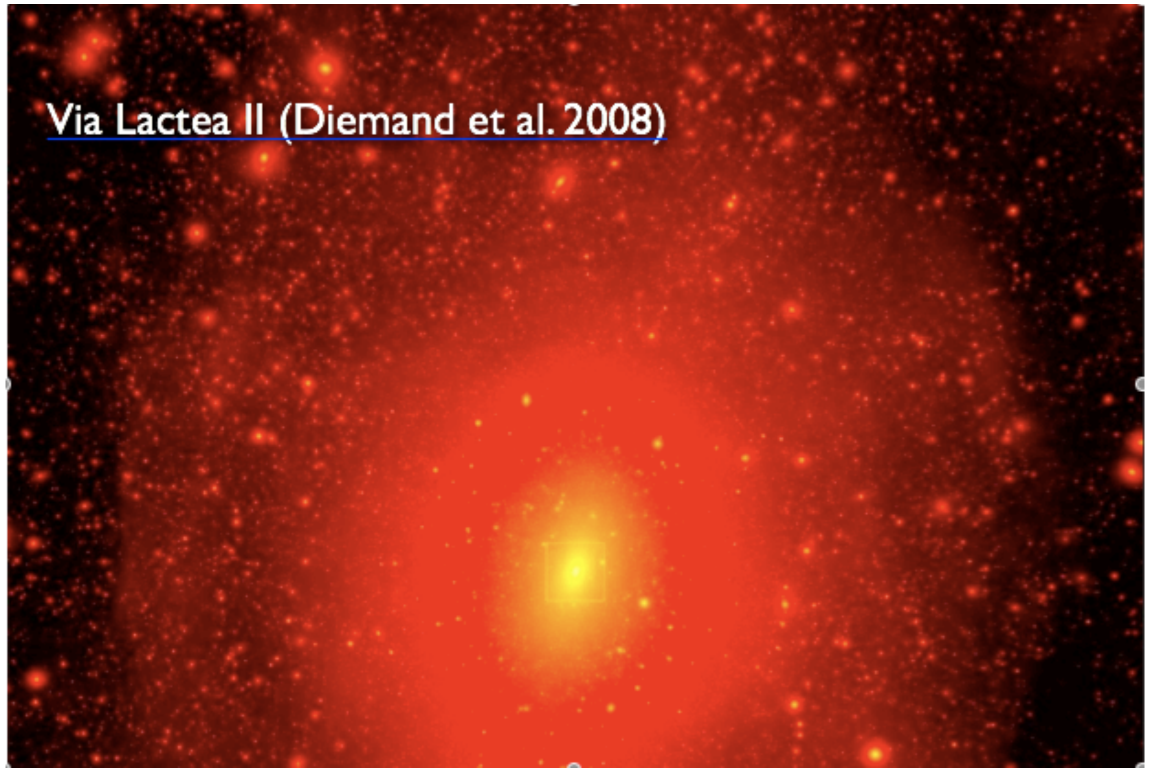


Additional Work is required before drawing any conclusions regarding DM.
- Effective Area Sys.
- Systematic Uncertainties with diffuse emission.
- Unresolved sources
- Instrumental effects

Work is continuing!



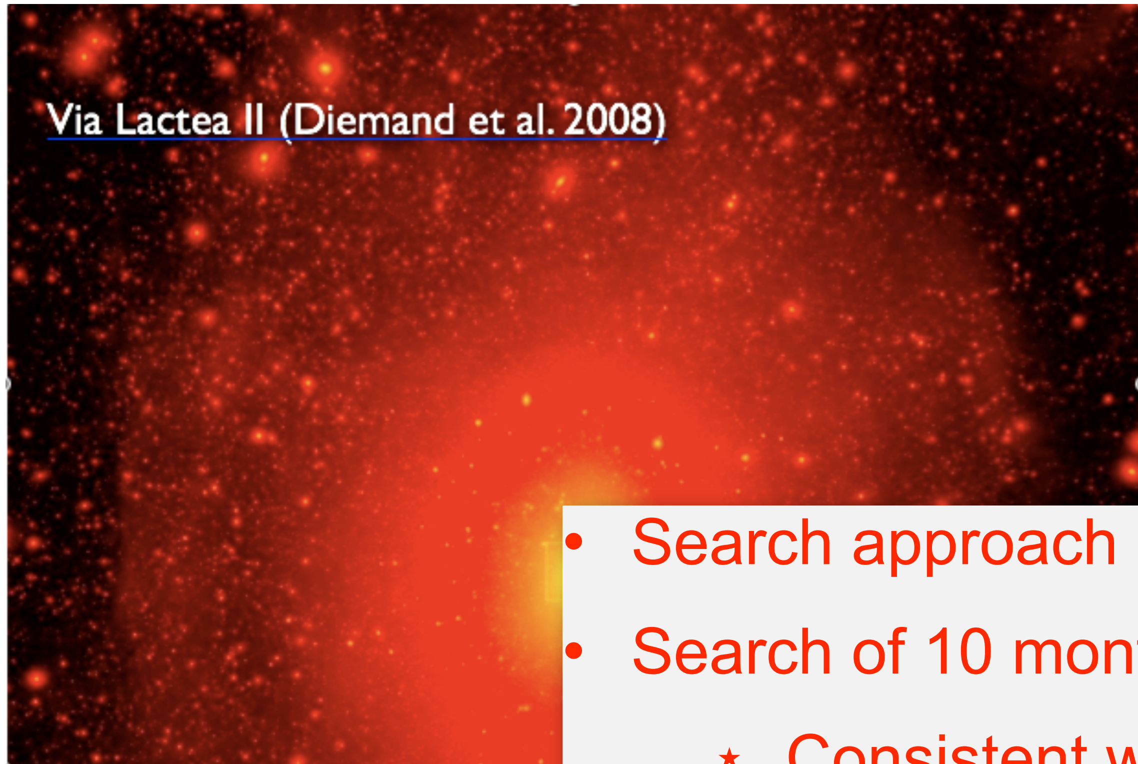
Search for DM "Clumps"



- Expect Clumps of DM in the Halo
- Characteristics:
  - ⋆ No significant counterparts
  - ⋆ Constant Emission
  - ⋆ Spatially Extended (~1 deg)
  - ⋆ DM Spectrum, not power-law

- Search for 5σ sources meeting the following criteria:
  - ⋆ More than 10^{o} from galactic plane
  - ⋆ No appreciable counter part in other wavelengths
  - ⋆ Spatially Extended: (Average nearby clump ~1^{o} radial extension)
  - ⋆ Spectrum consistent with DM (either b-bbar or $\mu^+\mu^-$)
  - ⋆ Emission constant in time (~1 week interval)
- Background sources+diffuse γ-ray emission

Search for DM "Clumps"



- Expect Clumps of DM in the Halo
- Characteristics:
  - ⋆ No significant counterparts
  - ⋆ Constant Emission
  - ⋆ Spatially Extended (…

- Search approach optimized on first three months data.
- Search of 10 months of data: **no candidates (Preliminary)**
  - ⋆ Consistent with expectations for 100 GeV WIMP, Via Lactea II, and $<\sigma v> = 3 \times 10^{-26}\ cm^3\ s^{-1}$.
- Continuing to analyze additional data and evaluate sensitivity to other models.
- Paper in preparation

- Search for …
  - ⋆ More …
  - ⋆ No ap…
  - ⋆ Spati…
  - ⋆ Spectrum consistent with DM (either b-bbar or $\mu^+\mu^-$)
  - ⋆ Emission constant in time (~1 week interval)
- Background sources+diffuse γ-ray emission

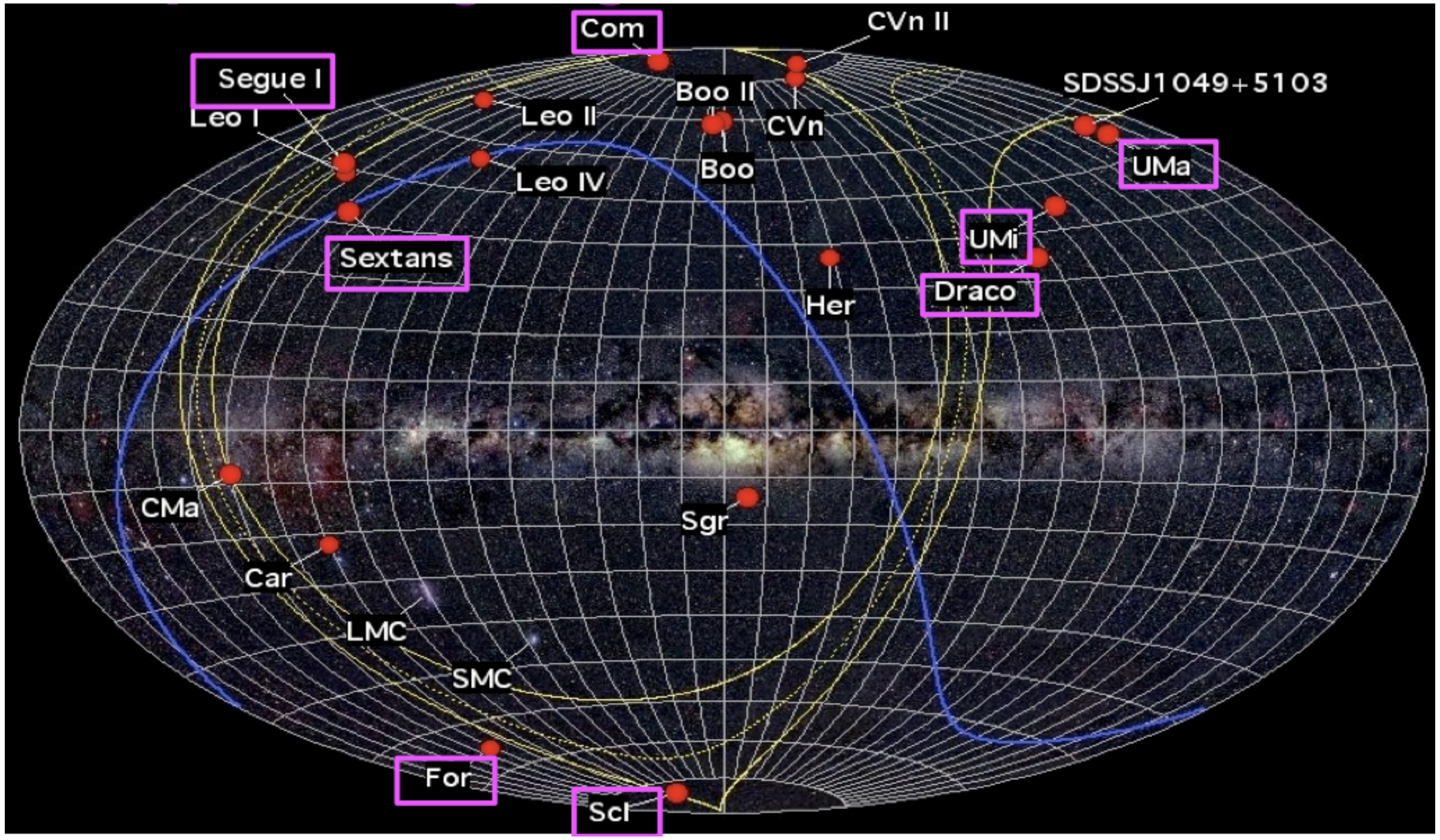
Dwarf Spheroidal (dSph) Galaxies

- dSphs are excellent DM targets of opportunity.
  - ★ N-Body DM Simulation predicts large clumps that support star formation.
  - ★ Very high Mass/Light Ratio (Dark Matter dominated)
  - ★ Low content of gas and dust (low astrophysical gamma-ray sources)
  - ★ Many close by (<100 kpc)
- Consider the 14 targets for Fermi (e.g. high gal. lat.)

Astrophys. J. **712**, 147 (2010)

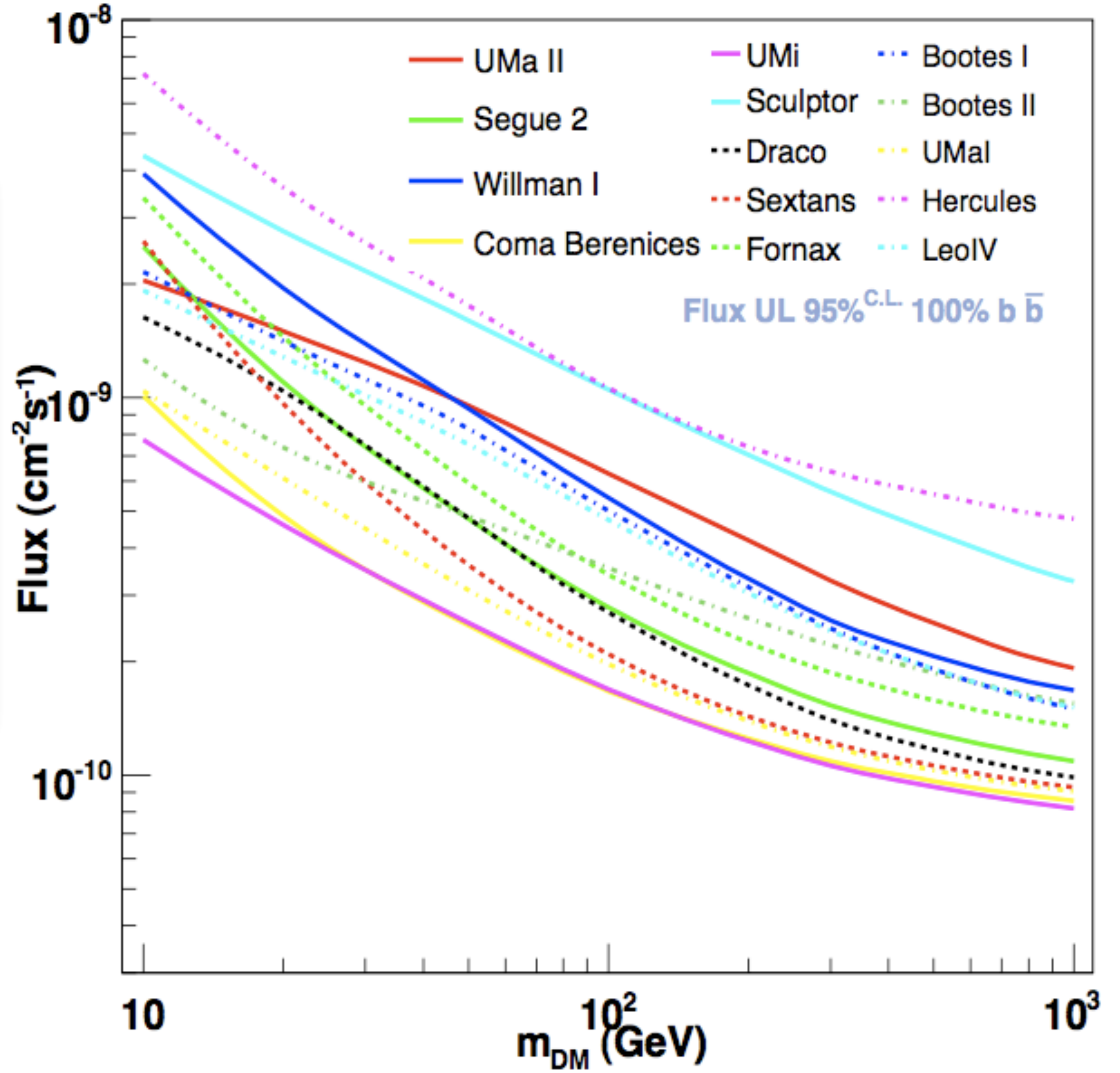
arXiv preprint: 1001.4531

- 11 month data set
- 100 MeV < E < 50 GeV
- dSph will be point-like.
- Backgrounds
  - ★ Existing point-like sources
  - ★ Galactic Diffuse



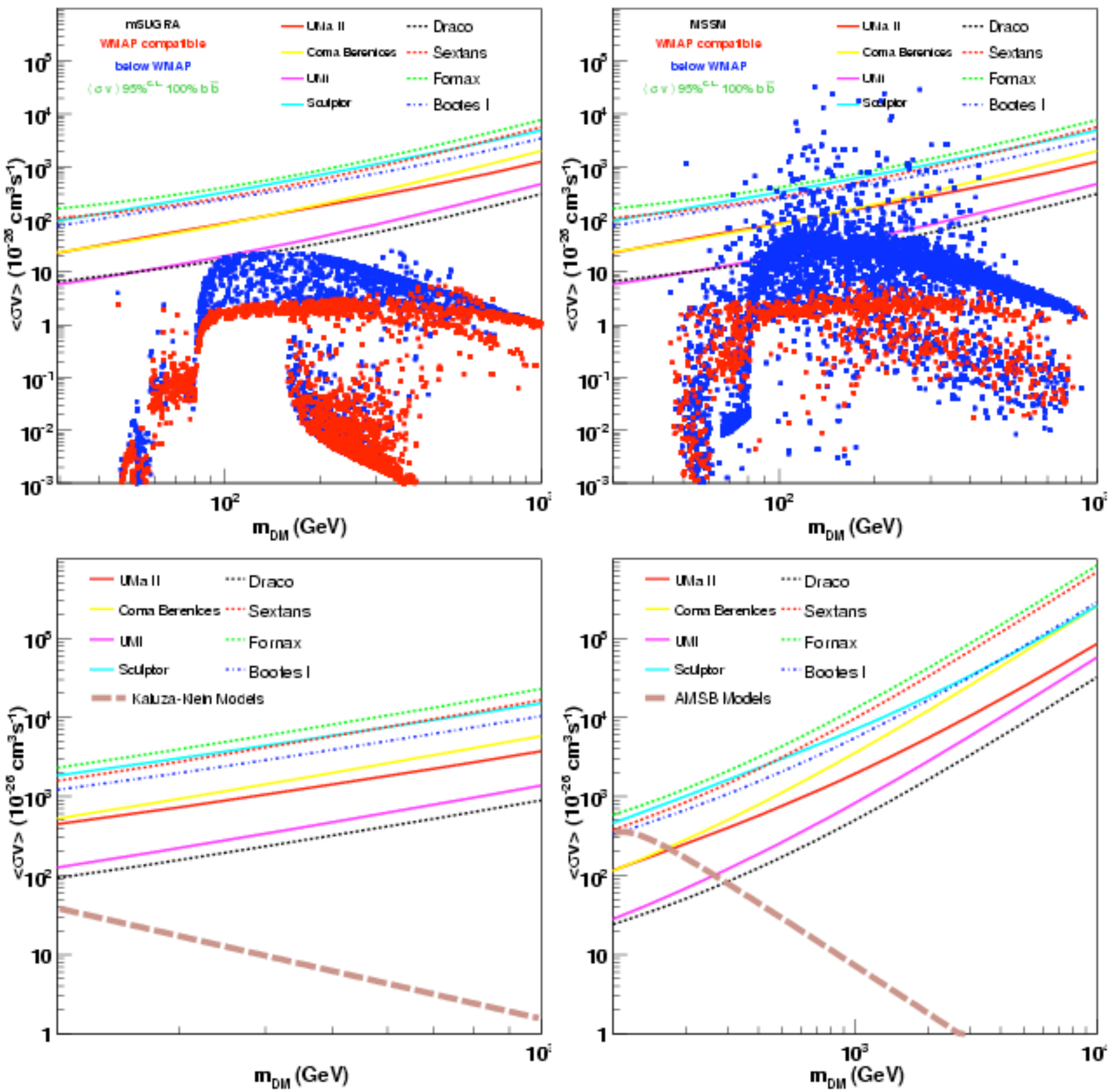
Limits from dSph Galaxies

- No excess of events was detected for any of the dSph.
- Set 95% CL upper limits on flux from the sample.
- For 8 of the 14, the flux limits are combined with DM density inferred from stellar data(*) to constrain dark matter models.



(*) stellar data from the Keck observatory (by Martinez, Bullock, Kaplinghat)

Limits from dSph Galaxies



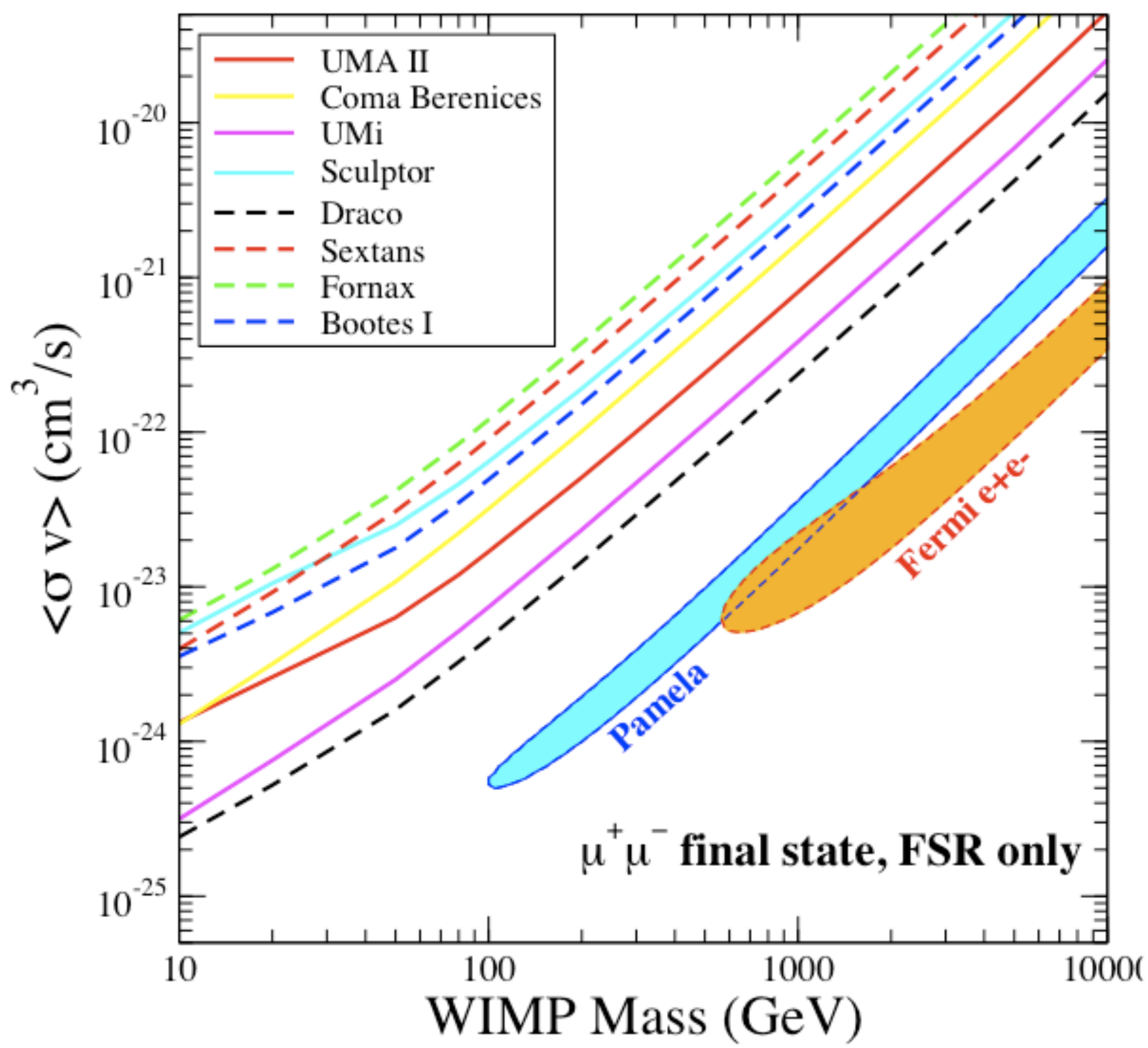
Beginning to constrain some of the models!

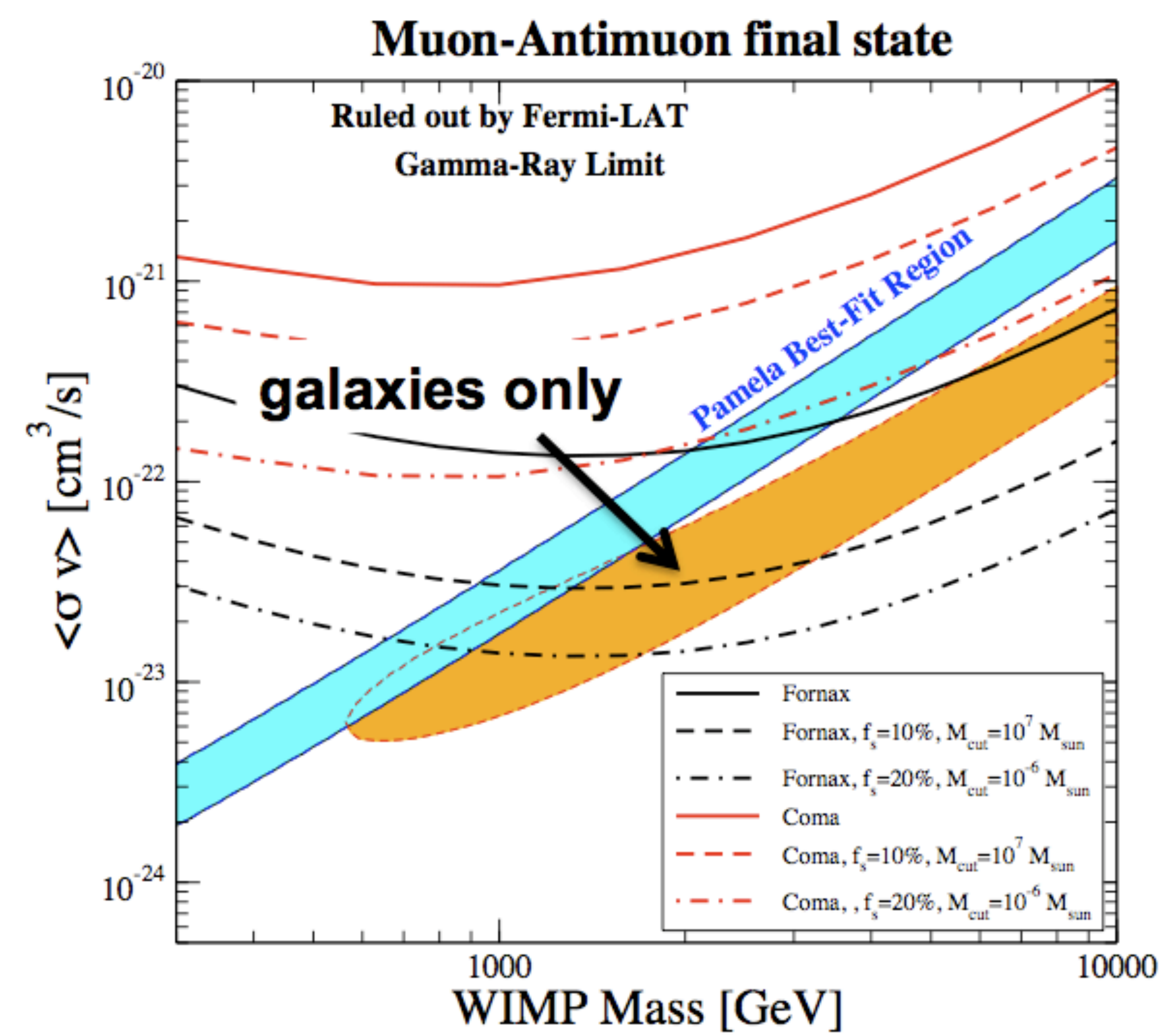
Limits from dSph Galaxies

- Can also consider WIMP annihilation to leptonic final states.
- Constraints from non-detection of galaxy clusters can place strong limits on leptophilic DM models.

Accepted for publication JCAP

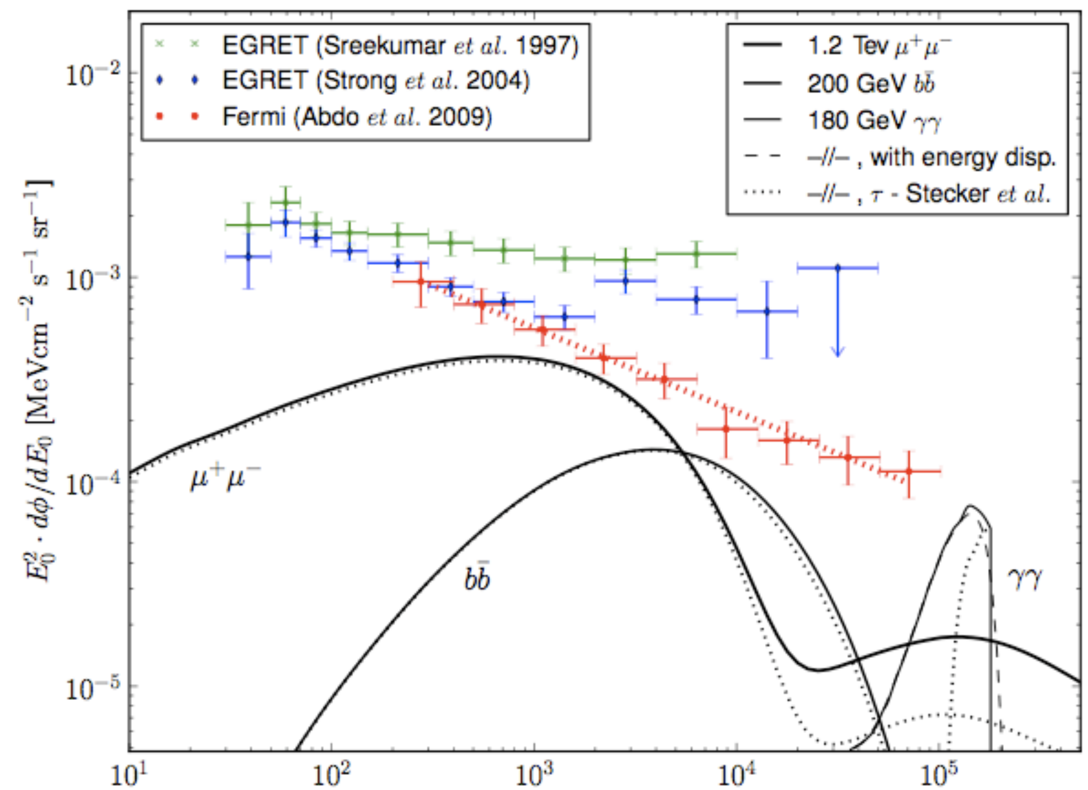
arXiv preprint: 1002.2239





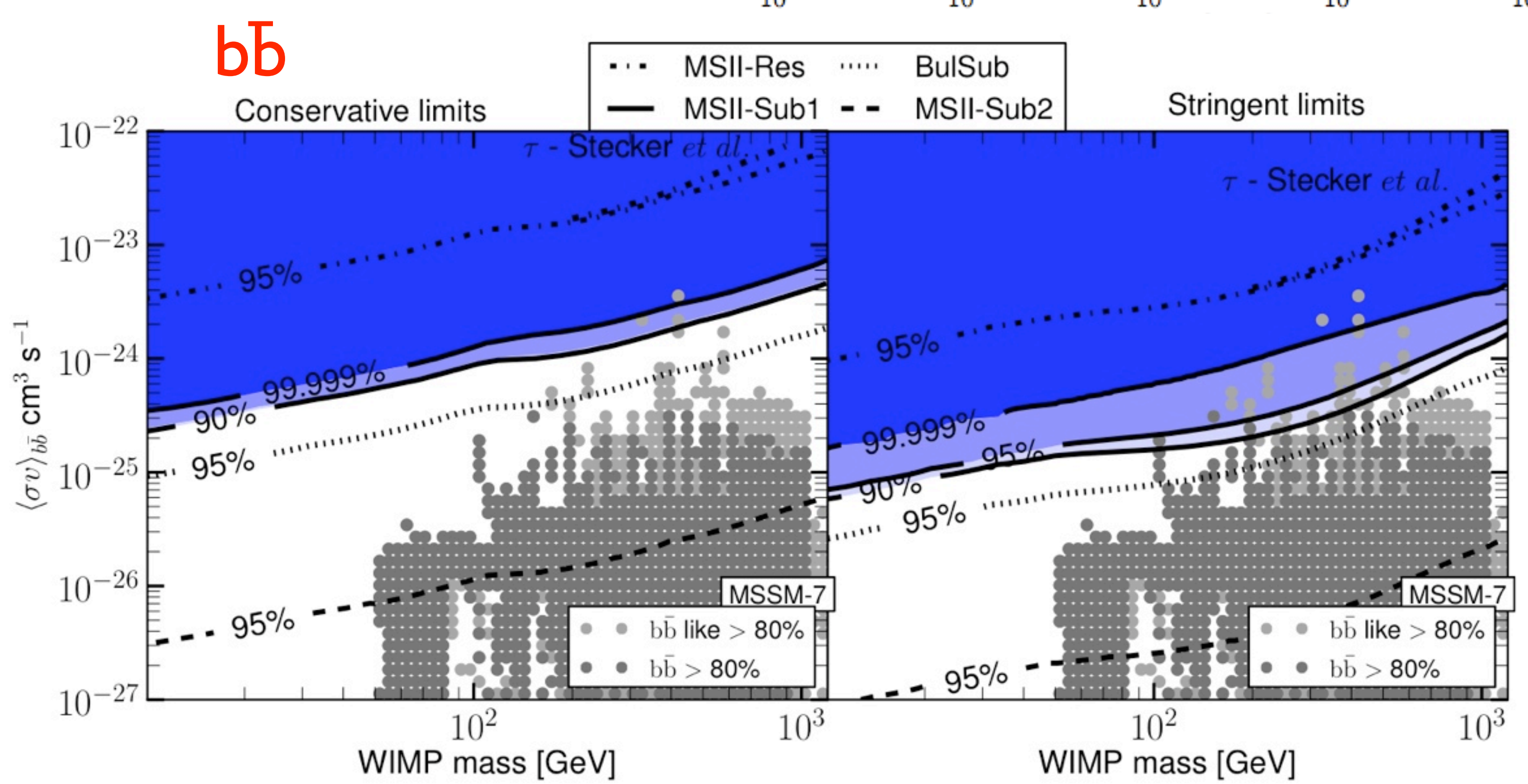
Cosmological DM Search

- Halos of other galaxies at all distances are shining in gamma-rays.
- Limits can be set based on Fermi's measurement of the the isotropic diffuse gamma-ray emission.
- Uncertainties associated with the evolution of DM structure



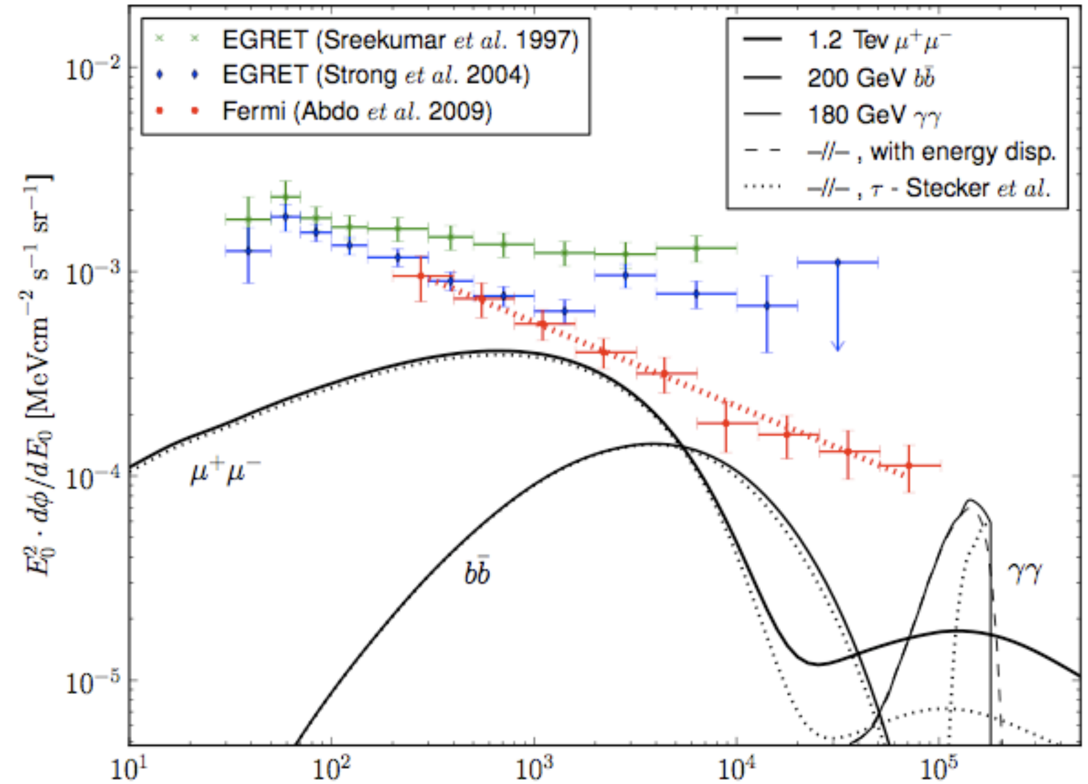
JCAP 1004:014,2010.

arXiv preprint: 1002.4415



Cosmological DM Search

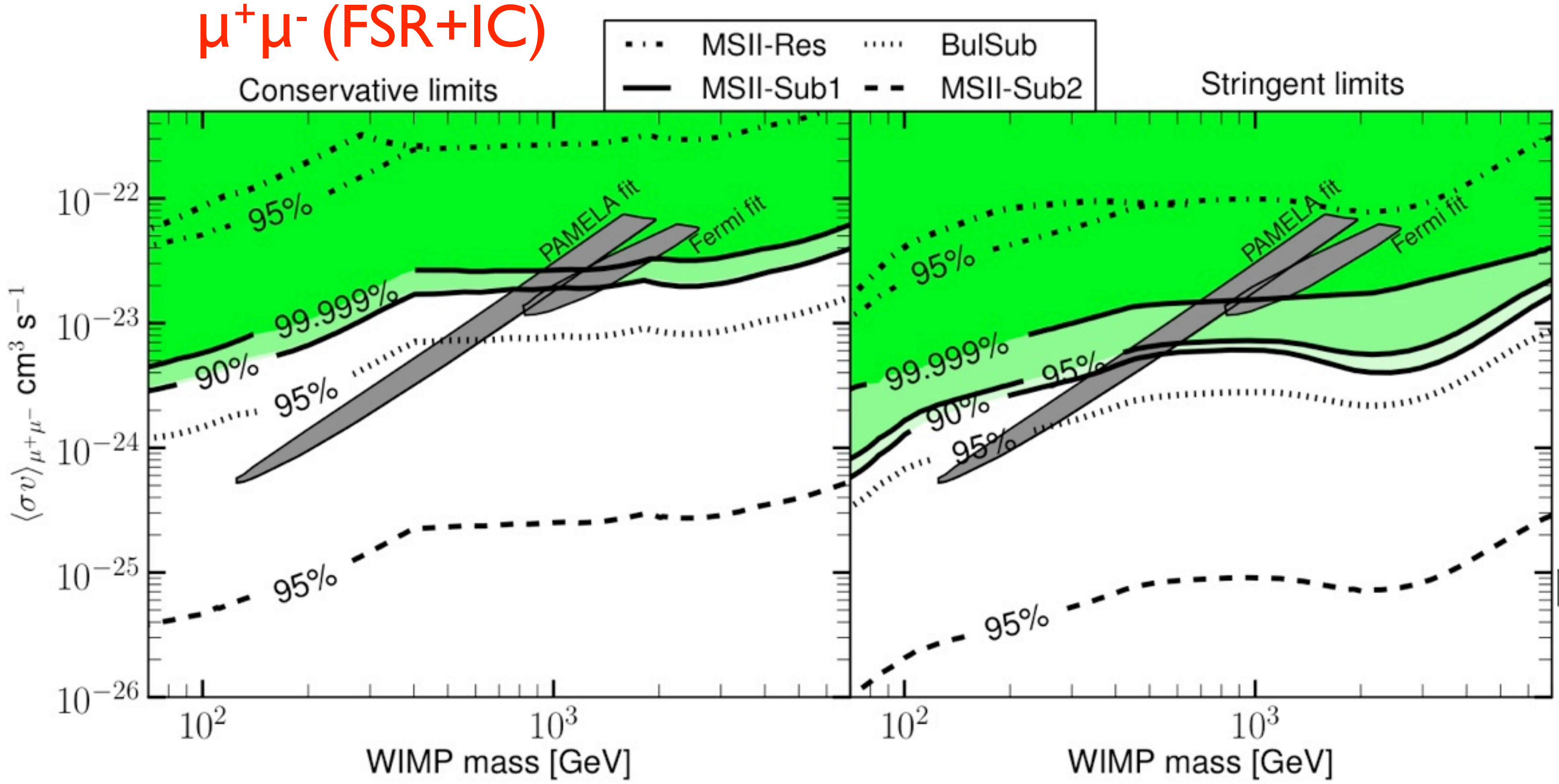
- Halos of other galaxies at all distances are shining in gamma-rays.
- Limits can be set based on Fermi's measurement of the the isotropic diffuse gamma-ray emission.
- Uncertainties associated with the evolution of DM structure



JCAP 1004:014,2010.

arXiv preprint: 1002.4415

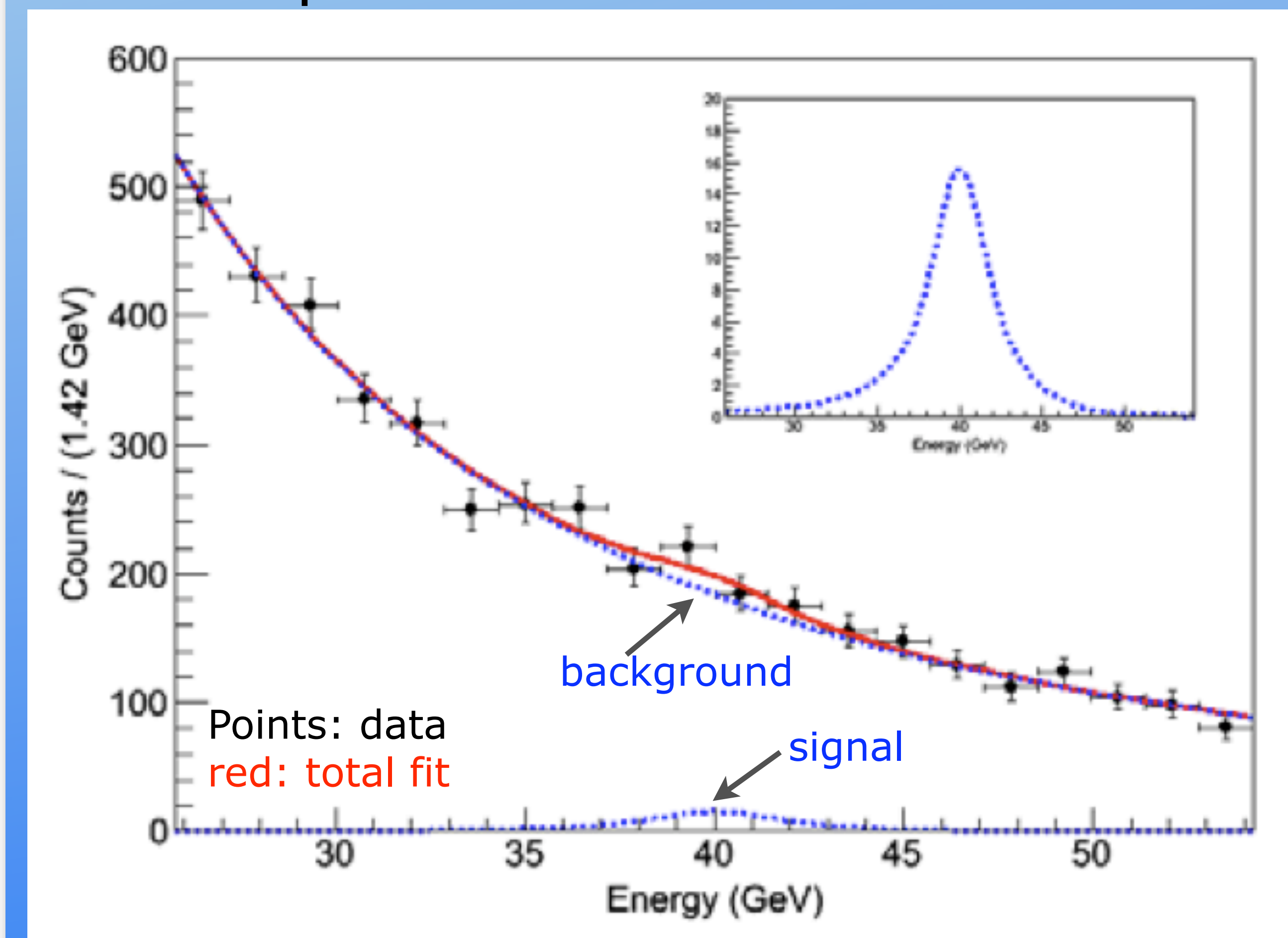
$\mu^+\mu^-$ (FSR+IC)

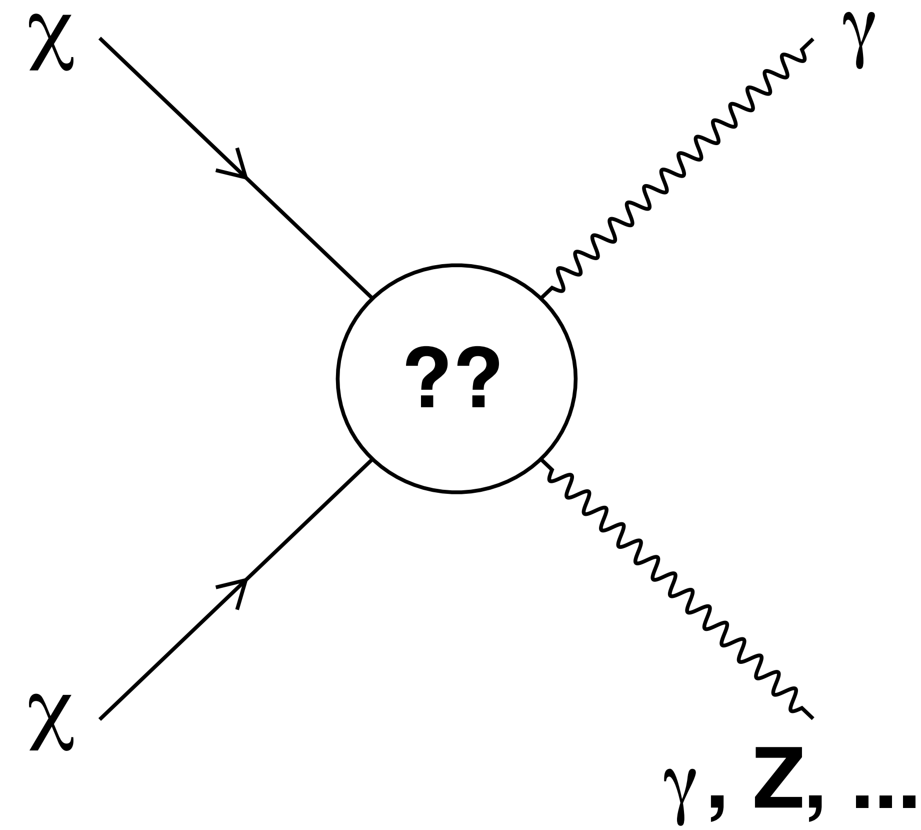


Searching for Dark Matter Gamma Ray Lines

- ***"Smoking Gun" Signal***
- Expected Branching fraction Small
    - Typically 10^{-1} to 10^{-4}
- Energy Resolution is key!
- Instrument resolution ~10% at 100 GeV
- Scan energy (30-200 GeV) looking for a bump.

Example fit for a 40 GeV line





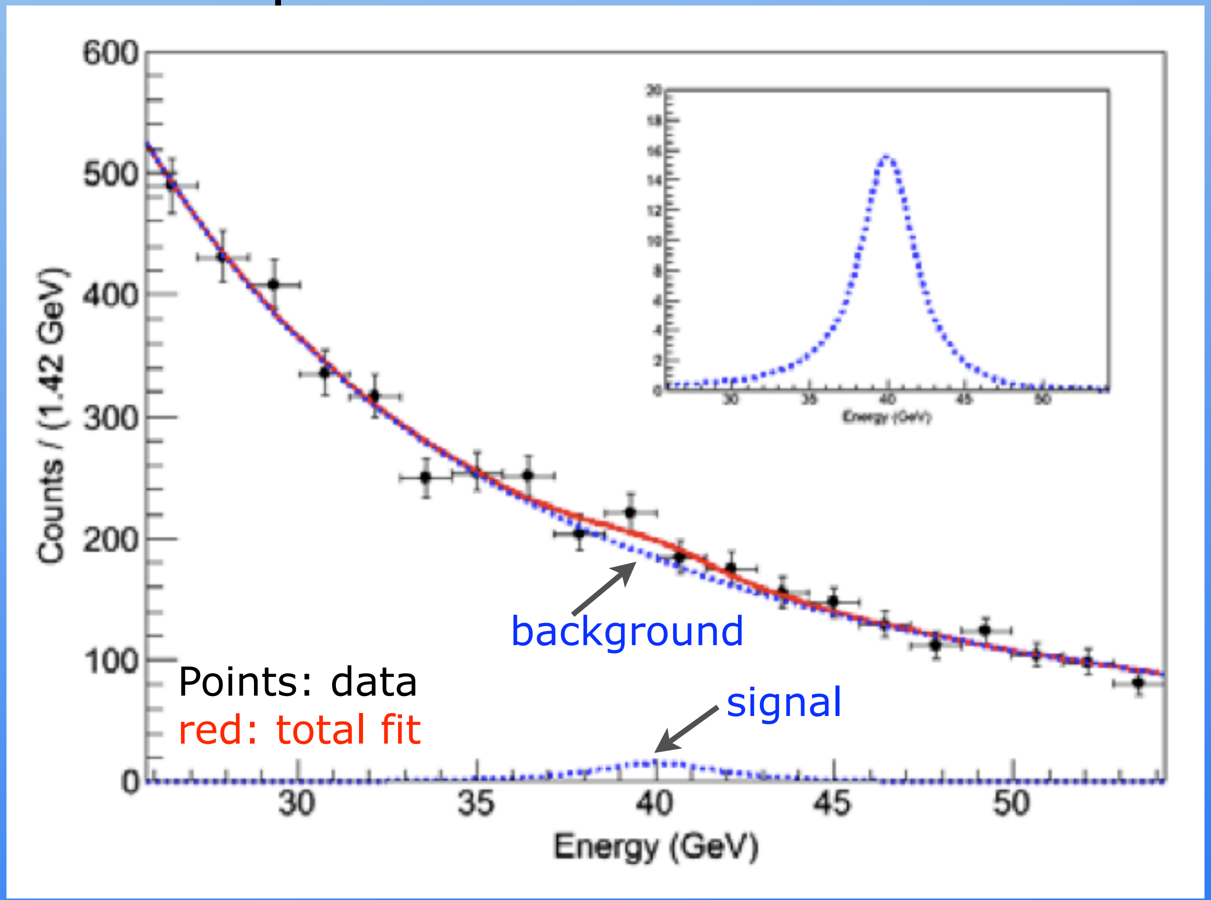
Final State $\gamma\gamma \rightarrow E_\gamma = M_{DM}$

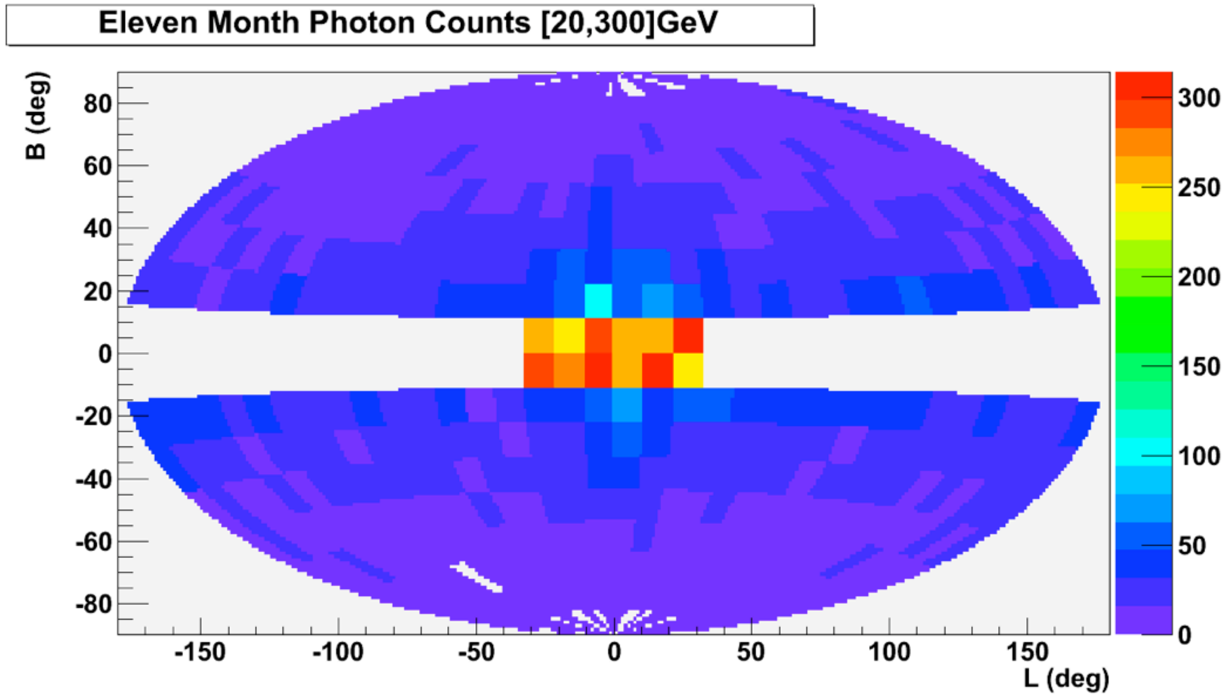
Final State $\gamma Z \rightarrow E_\gamma = M_{DM} - \frac{M_Z^2}{4M_{DM}}$

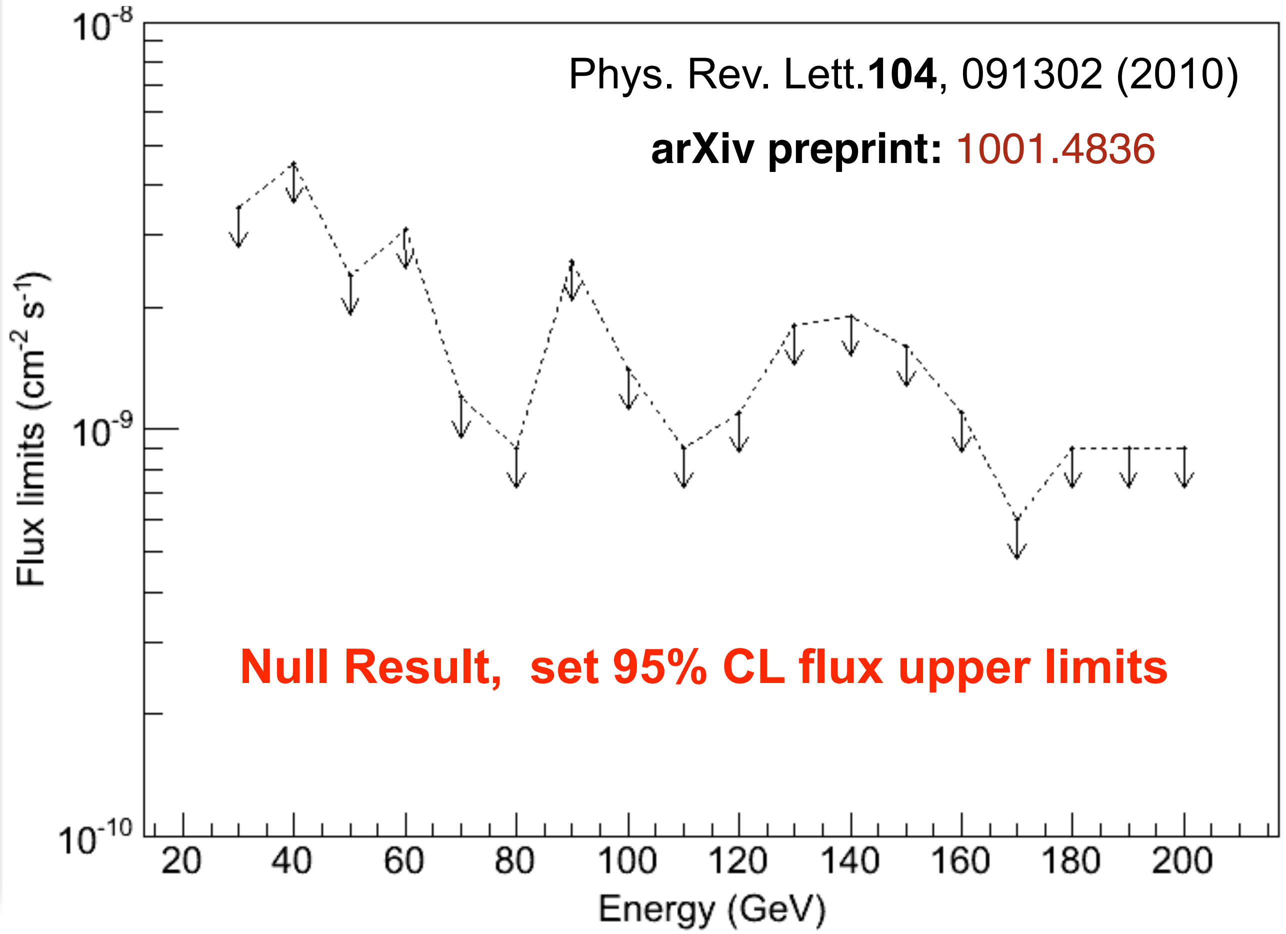
Searching for Dark Matter Gamma Ray Lines

- 11 month data sample
- Signal Model is line smeared by LAT response function.
- Background is power-law fit to side-bands
- Search Region:
    - |b|>10º and 20º x 20º around GC
- Remove sources (|b|>1º).

Example fit for a 40 GeV line

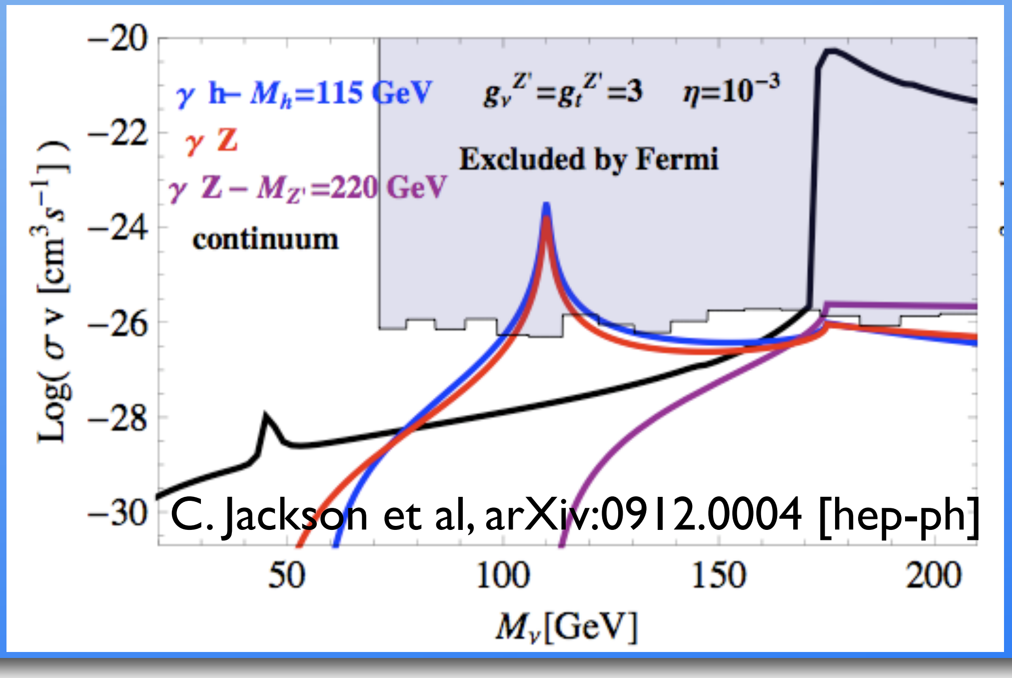


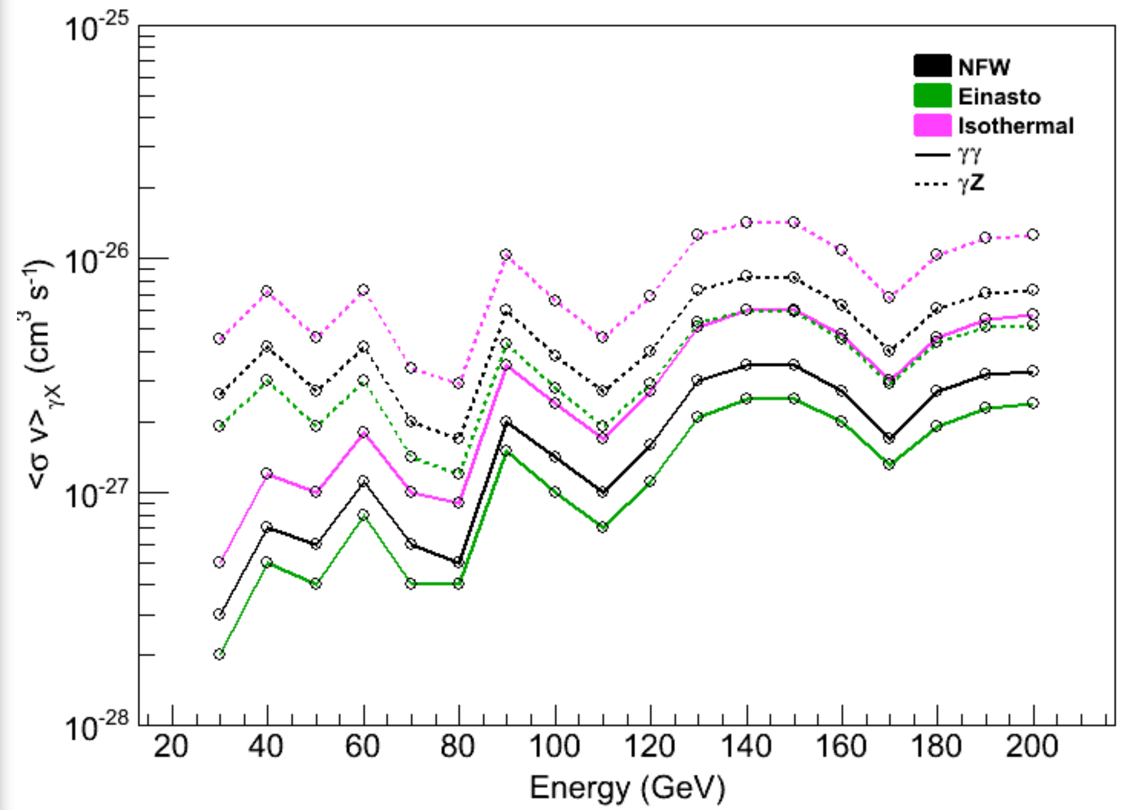


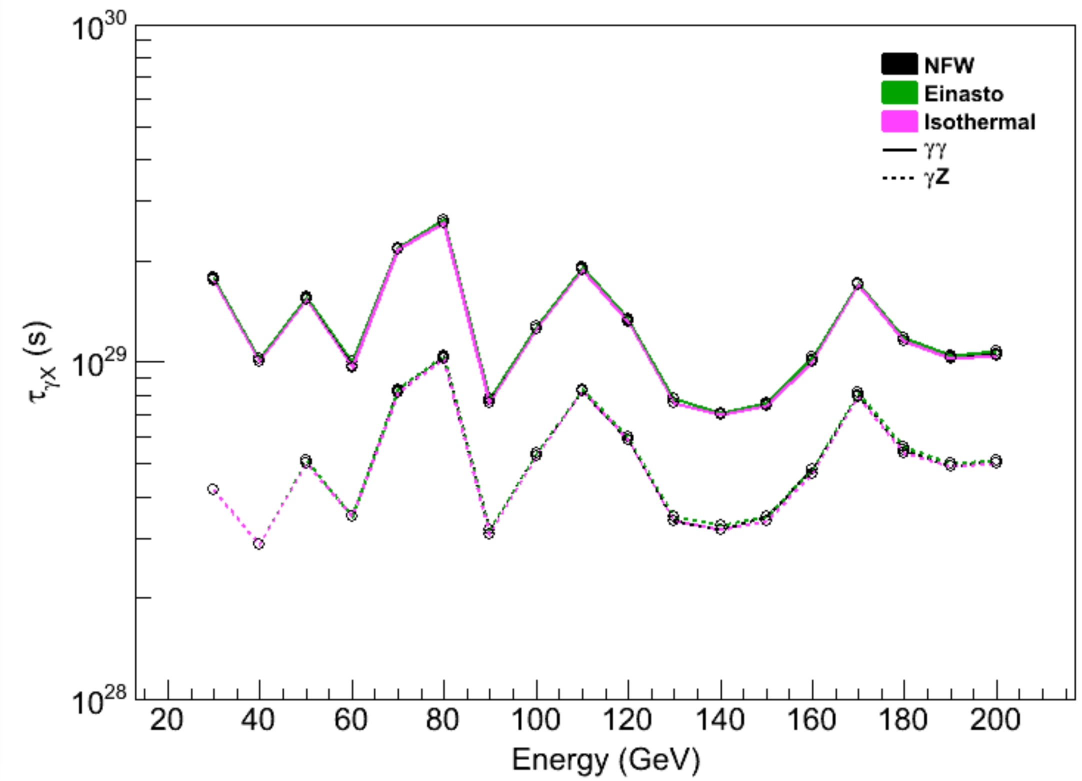


Searching for Dark Matter Gamma Ray Lines

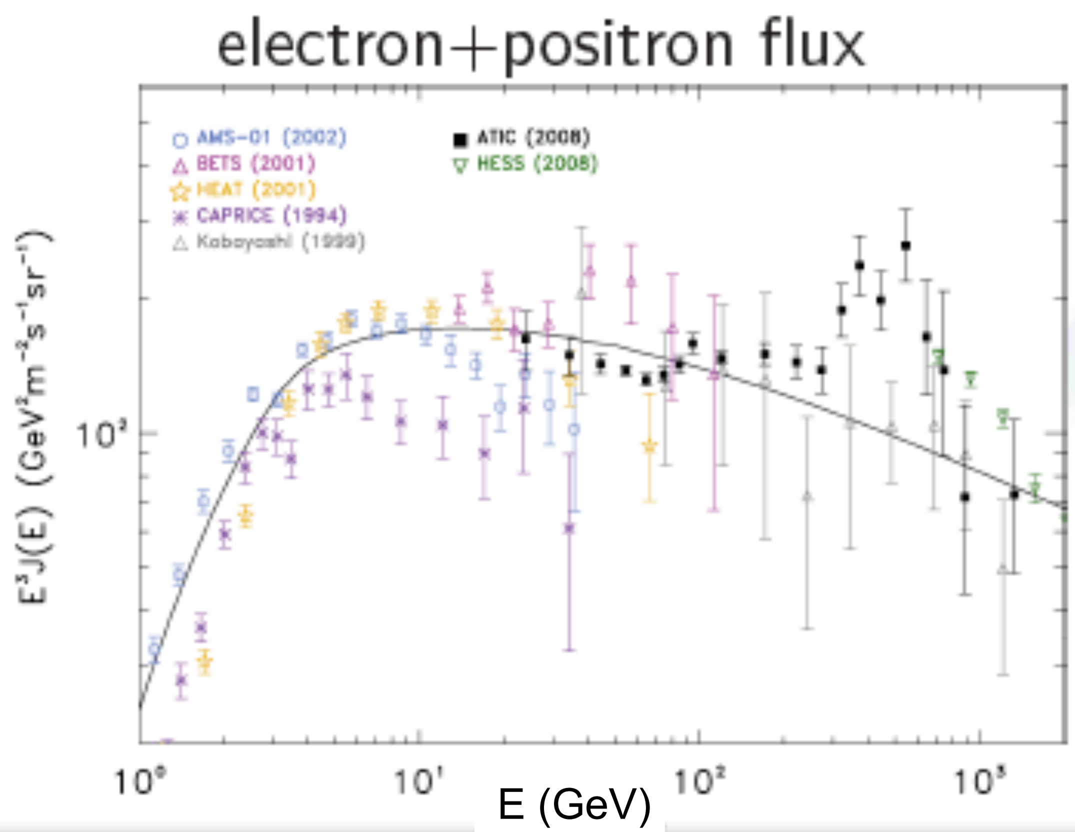
- Assuming DM density distribution, we can set limits on
  - Annihilation Cross Section
  - DM Lifetime for decay mode
- Limits still far from typical WIMP expectations.
- Some exotic models are disfavored
  - Models with non-thermally produced WIMPS can predict large <σ v>.
  - Some gravitino decay models have lifetime < 10^{29} s.
- Limits still far from typical WIMP expectations.
- Even limits on Higgs in Space!

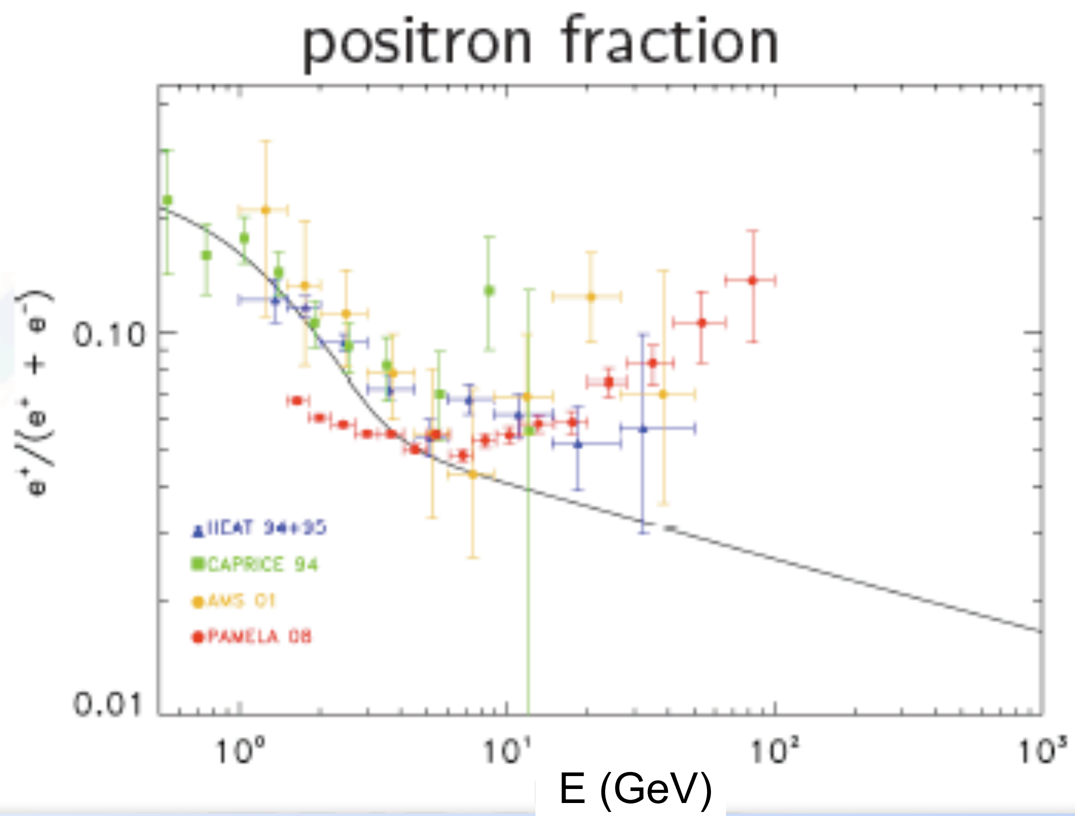






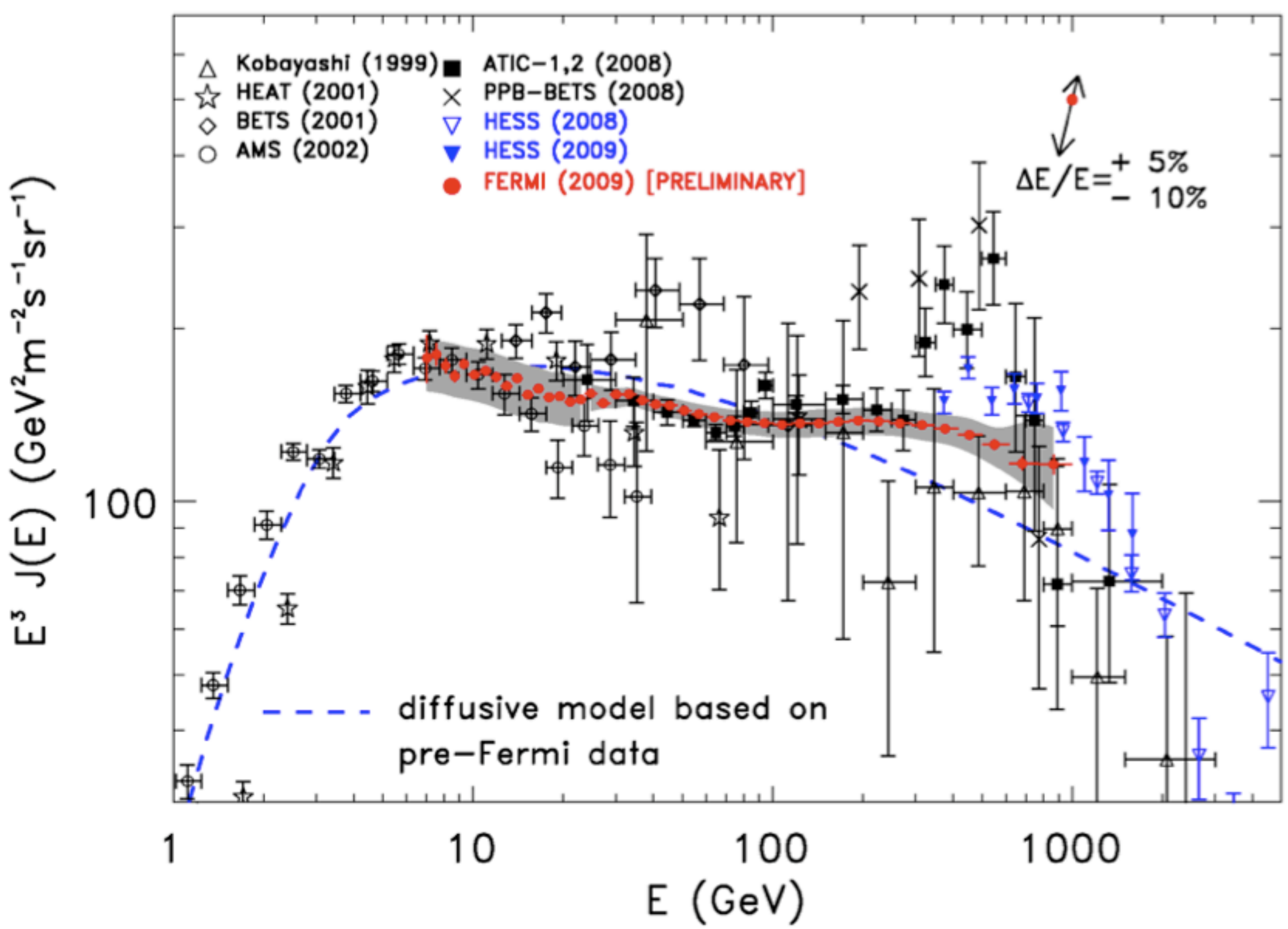
Interesting Features of Cosmic Ray Electrons





- Spectral Features:
  - ★ ATIC excess around 600 GeV
  - ★ H.E.S.S possible cutoff around 1 TeV
- Pamela shows excess in positron fraction
- Lots of new papers on the subject!
- <u>Fermi LAT is an excellent electron/positron detector.</u>

Resulting Fermi Electron Spectrum



- Excellent Statistics: ~4.5M evts
  - >400 elec 0.772 - 1 TeV
- No Evidence of prominent spectral feature seen by ATIC.
  - ATIC excess 300-800 GeV: 70 e
  - Fermi would expect ~7000 e
- Fermi Data not compatible with prelaunch expectation from diffuse galactic emission.
  - Diffuse model can be modified.
  - **Doesn't account for positrons**

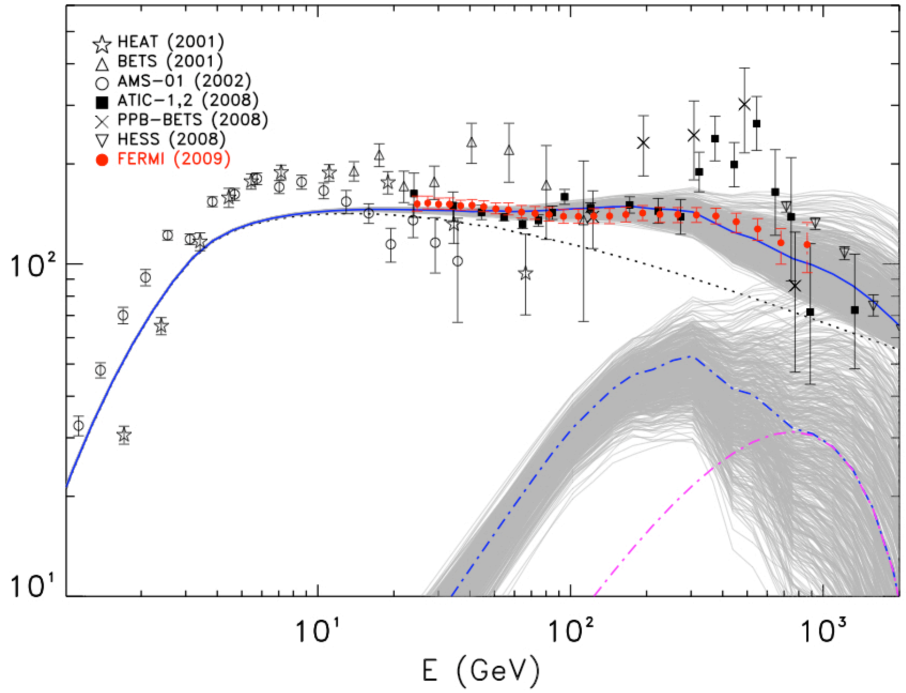
Measured spectrum well described by **power-law** within current values of **systematic** errors

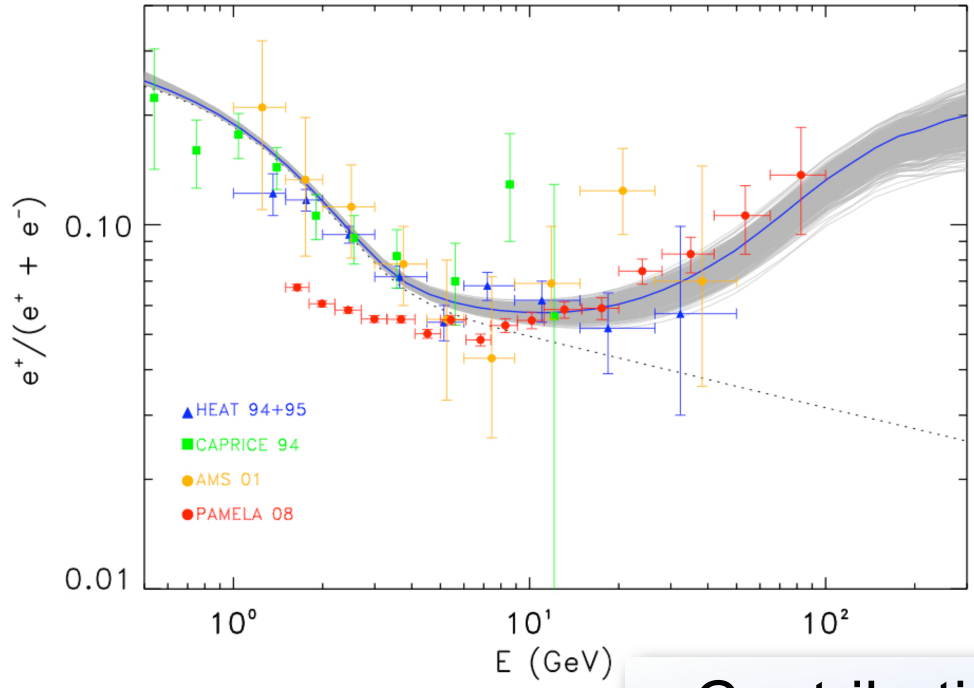
$$J_{e^\pm} = (175.40 \pm 6.09) \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-(3.045 \pm 0.008)} \mathrm{GeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

with χ^2 per degree of freedom of 9.7 / 23

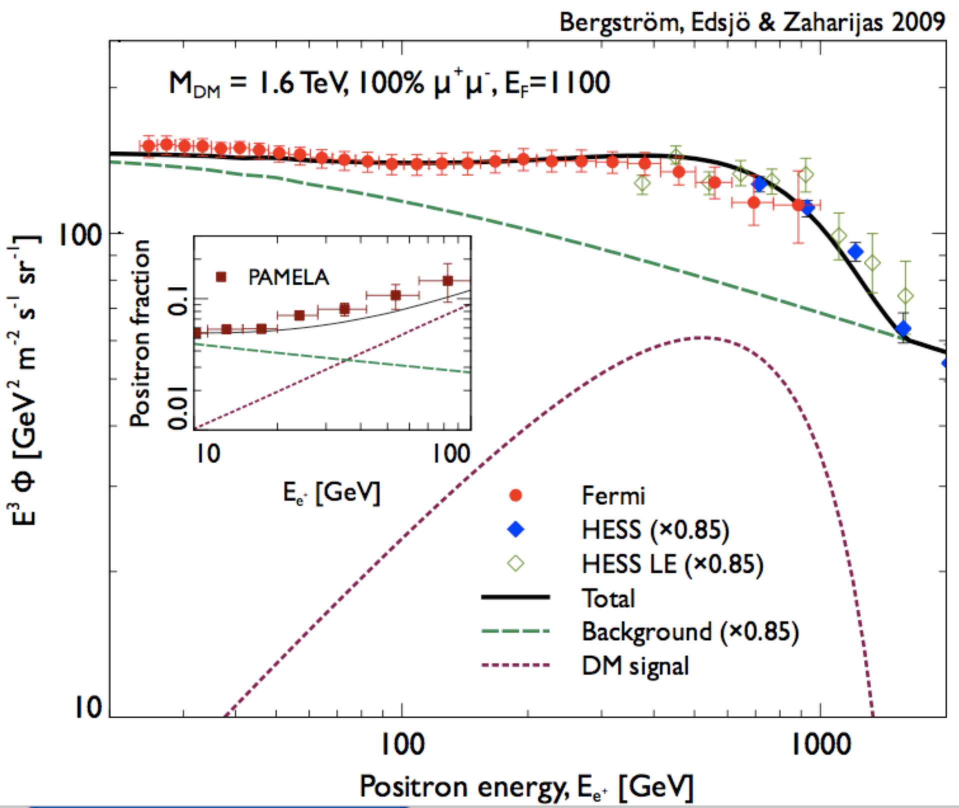
Possible Explanations

arXiv:0905.0636 [asto-ph.HE]





Grey Lines: Possible contribution with varied parameters (injection index, cutoff energy, etc.)
Blue dot-dash: Representative choice of parameters.
Blue Solid: Diffuse Model + Pulsars



- Contributions from nearby, age appropriate, pulsars.
  - ★ From ATNF Catalog
- Provides a reasonable modification to the electron spectrum.
- Also, modifies the position fraction in a reasonable fashion.

- DM also can provide an explanation
- DM answer typically requires substantial boost factors and preferential final states.

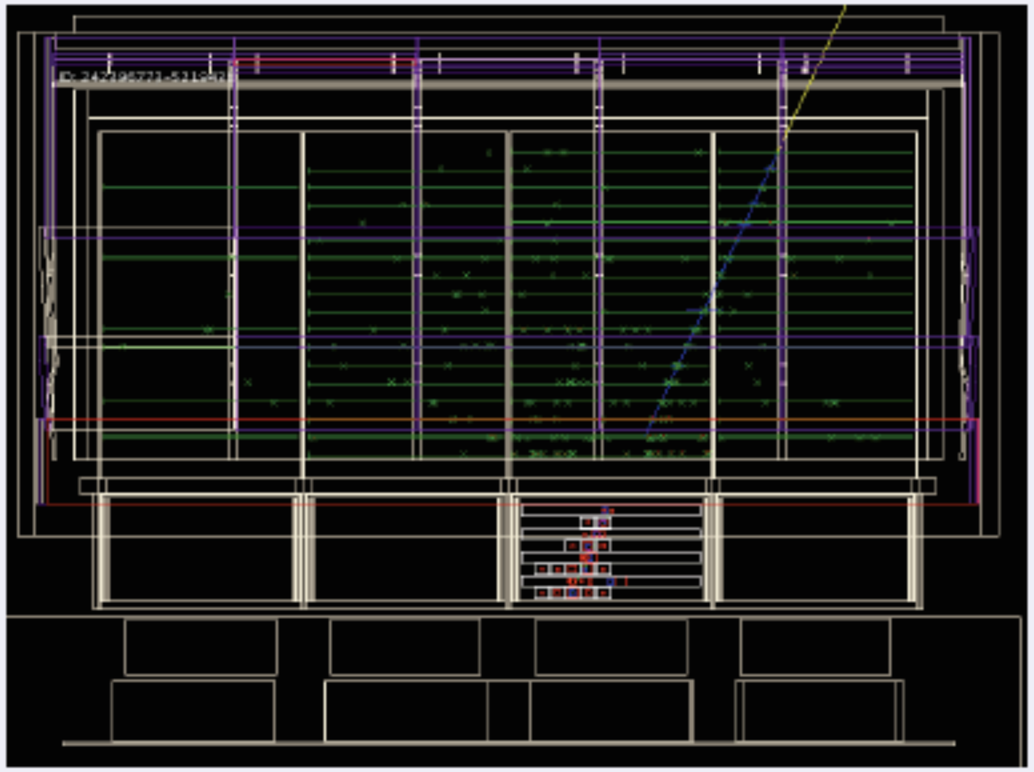
Summary

- Fermi has been working very well.
- Multi-pronged Searches for Dark Matter WIMPs
- No detection yet.
- Constraints are begin to get interesting.
- Intense work is continuing
  - ⋆ ***Especially in improving our understanding astrophysical backgrounds***
- **We have analyzed ~1 year of data.**
- **Expect a 5-10 year mission.**
  - ⋆ ***Hopefully most exciting results to come!***

Backups

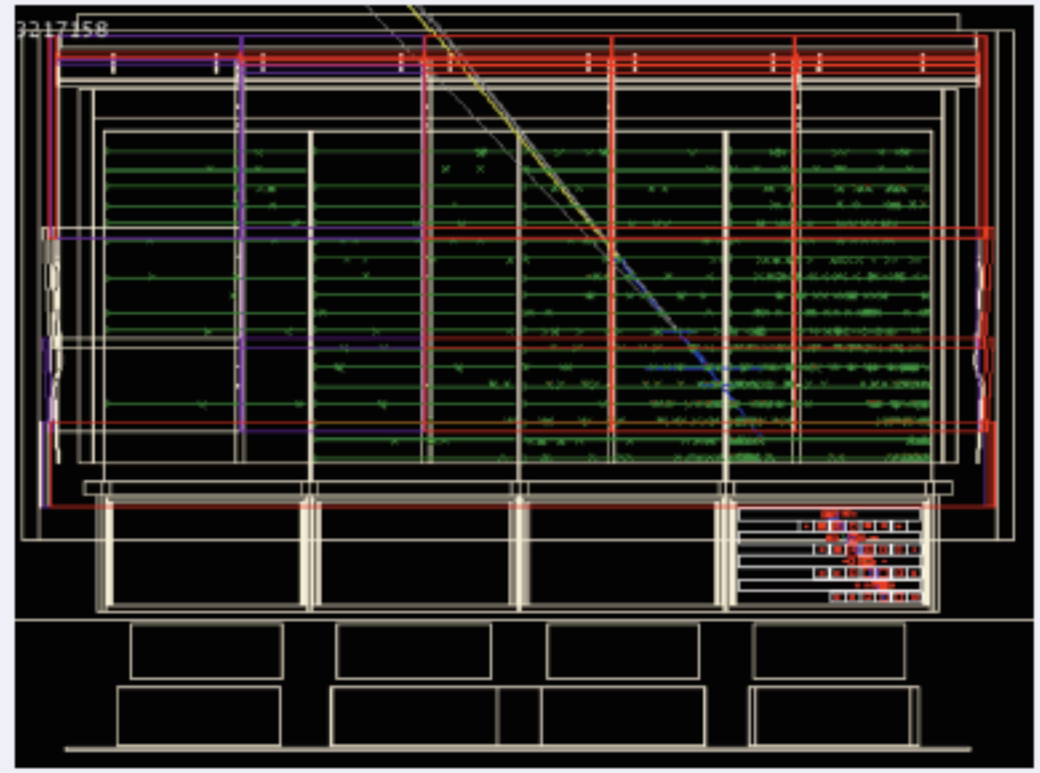
Electrons and Hadrons With Fermi

Electron candidate



- few ACD tile hits in conjunction with the track
- clean main track with extra-clusters very close to the track - note backsplash from the calorimeter
- well defined symmetric shower in the calorimeter, not fully contained

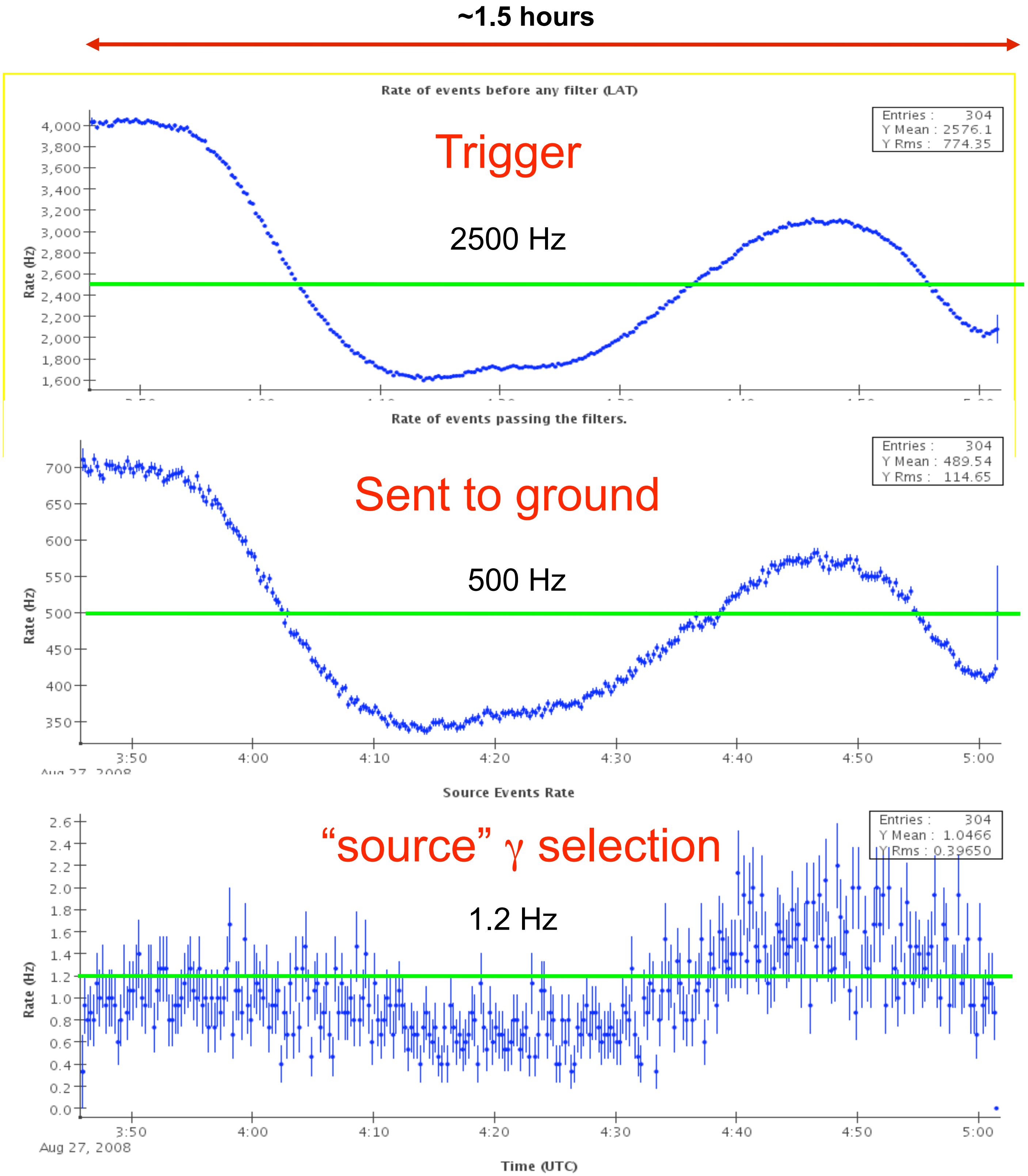
Hadron candidate



- large energy deposit per ACD tile
- small number of extra clusters around main track, large number of clusters away from the track
- large and asymmetric shower profile in the calorimeter

- LAT does not distinguish electrons from positrons
  - ★ For what follows: "electrons" means both
- All events with E > 20 GeV are sent to the ground.

On orbit rates in nominal configuration



- Overall trigger rate: ~few KHz
  - ✓ Substantial variations due to orbital effects
- Downlink rate: ~400—500 Hz
  - ✓ ~90% from GAMMA filter
  - ✓ ~20—30 Hz from DGN filter
  - ✓ ~5 Hz from HIP filter
- Rate of photons after the standard background rejection cuts for source study: ~1 Hz
  - ✓ Most of the downlinked events are in fact background, final 100:1 rejection is done in ground processing.